

Assessment of Water Quality of River Ganga in Haridwar Using Benthic Macro-Invertebrates as Bio-Indicators

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Abstract: River water quality is a key indicator of ecological health, biodiversity and sustainability of freshwater resources. The River Ganga, especially the section through Haridwar (Uttarakhand), is ecologically, culturally and socio-economically significant. A growing number of human activities such as urbanization, religious bathing, tourism, and discharge of wastewater into the river require continuous evaluation of river health. While conventional physicochemical parameters give information about the water at the time of sampling, biological indicators can give an indication of the cumulative effects of environmental stress over time.

The present study of the present work aims to find out the water quality parameters of River Ganga in Haridwar through the help of benthic macro-invertebrate as bio-indicator. The study design explores the diversity and abundance of benthic macro-invertebrates, their taxonomic composition and their distribution at the various sampling sites. In the proposed assessment, a range of physicochemical parameters such as temperature, pH, dissolved oxygen, biochemical oxygen demand, conductivity and turbidity are also taken into account, in addition to the biological ones. In areas where there are well-defined regional scoring criteria, the Biological Monitoring Working Party (BMWP) approach, taxonomic richness and diversity indices are used to interpret biological water quality. Special emphasis is placed on the pollution-sensitive groups (some of the mayflies and caddisflies) and relatively pollution-tolerant groups (some of the chironomid larvae and the aquatic worms). The relevance of biological monitoring in the Ganga in Uttarakhand has been established by earlier studies in the area where the effects of the local wastes on the macro-invertebrate community have been shown to be measurable.

The study aims to offer a biological viewpoint to river health and facilitate identification of areas in need of more intensive monitoring and pollution control. Water-quality classifications must be based on field sampling, laboratory analysis and statistical evaluation..

Keywords: River Ganga, Haridwar, benthic macro-invertebrates, bio-indicators, water quality, biological monitoring, BMWP, aquatic ecosystem

I. INTRODUCTION

Water is a vital natural resource, contributing to human wellbeing, biodiversity, agriculture and economic development. Rivers are important for the maintenance of ecological balance because they are a source of freshwater, habitat for aquatic organisms, and support human activities. But urbanisation, population growth, tourism, religious activities, and discharge of waste water are increasingly endangering the quality of river water and aquatic life.

River Ganga is one of the most important river system of India with significant ecological, cultural and economic value. The Haridwar section is of special significance due to the high level of religious activity, bathing, tourism and



urbanization. The activities bring attention to the importance of ongoing monitoring to keep the river in good ecological and water quality.

The traditional assessment of water quality includes physicochemical parameters (temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), turbidity, and electrical conductivity (EC). While these will give the essential parameters of the water conditions, they may not be suitable to represent the total environmental stress experienced over a period of time. Thus, biological monitoring has become a popular technique as a complementary method of assessing aquatic ecosystem health.

Bio-indicators are widely used and include benthic macro-invertebrates (aquatic insect larvae, molluscs, annelids and crustaceans) which are sensitive to environmental change in terms of distribution, abundance and diversity. Pollution sensitive taxa are generally good ecological indicators, while some pollution-tolerant taxa can become dominant when the water is enriched with organic matter or oxygen is depleted.

Agrawal et al. (2019) evaluated the biological water quality of Ganga river in Uttarakhand based on benthic macro-invertebrates and found variations in the water quality of the river due to the wastewater related impacts. To carry out this study, the present study tries to assess the water quality of Haridwar by using the index of water quality based on macro-invertebrate community analysis along with physicochemical measurement to help in the proper conservation and management of river.

II. LITERATURE REVIEW

Thakur et al. (2024)¹ studied the macrobenthic invertebrates and community structure at nine sites in the upper and middle reaches of River Ganga. The study was carried out in the period March 2017 to January 2020 and recorded 35 taxa of 29 families and 16 orders. Both the researchers and the insects observed that insects were the dominant organism at some sites in the upper reaches, while gastropods and bivalves were more numerous at some sites in the middle reaches. They reported that distribution of the macro-invertebrates was affected by habitat characteristics, environmental factors and anthropogenic activities. This research emphasises that both abiotic and biotic assessment must be taken into account when assessing the health of a river site.

Simaika et al. (2024)² have done a literature review on fresh water biodiversity monitoring and biological assessment programmes based on benthic macro-invertebrates. They analysed data from 110 respondents from 67 countries and highlighted relevant concerns related to sampling methodology, specimen identification, biological metrics, assessment methodology, and coordination of monitoring programmes. The authors highlighted the importance of harmonised protocols for enhancing the comparability and reliability of freshwater assessments. The results obtained by them can also be used in the present study because standardised sampling and taxonomic identification of the living organisms are important to get the reliable results in assessing the water quality of Haridwar stretch of Ganga.

The abundance and distribution of benthic macro-invertebrate families were studied along a stretch of River Ganga at 33 locations in Uttarakhand, Uttar Pradesh, Bihar and West Bengal by **Sharma and Behera (2022)³**. They determined

¹ Thakur, V. R., Verma, H., Jha, D. N., Alam, A., Kumar, J., Shukla Das, S. C., Verma, S. K., Mishra, S. K., Singh, U., & Das, B. K. (2024). An account of macrobenthic invertebrate assemblages and community structure from the River Ganga, India. *Journal of the Inland Fisheries Society of India*, 56(2), 133–144. <https://doi.org/10.56093/jifsi.v56i2.2024.163420>

² Simaika, J. P., Stribling, J., Lento, J., Bruder, A., Poikane, S., Moretti, M. S., Rivers-Moore, N., Meissner, K., & Macadam, C. R. (2024). Towards harmonized standards for freshwater biodiversity monitoring and biological assessment using benthic macroinvertebrates. *Science of the Total Environment*, 918, Article 170360. <https://doi.org/10.1016/j.scitotenv.2024.170360>

³ Sharma, J., & Behera, P. K. (2022). Abundance and distribution of aquatic benthic macro-invertebrate families of river Ganga and correlation with environmental parameters. *Environmental Monitoring and Assessment*, 194, Article 546. <https://doi.org/10.1007/s10661-022-10158-w>



that there were 15 families affected by pollution and 8 families that were not affected by pollution. The researchers found pollution-sensitive Ameletidae, but also noted pollution-tolerant families such as Chironomidae and Naididae at the study sites. They also explored macro-invertebrate diversity and the relationships observed between the physicochemical parameters such as pH, water temperature and dissolved oxygen. The use of taxonomic composition and environmental measurements to interpret biological water quality was shown to be valuable in the study.

The biological water quality was evaluated by the river Ganga using benthic macro-invertebrates at four sites in Patna stretch by **Goel et al. (2021)⁴**. A total of 1,523 organisms were recorded belonging to 11 orders and 43 families, during summer and late winter sampling. At two upstream sites, the researchers noted relatively good dissolved oxygen conditions and pollution sensitive Ephemeroptera families. The presence of Chironomidae at Fatuha was related to wastewater discharge, and a trend of decreasing Shannon–Wiener diversity index was noted at the downstream sites impacted by pollution. Results highlighted the need for seasonal sampling and the need to look at the biological diversity as well as the physicochemical parameters together to assess river water quality.

Agrawal et al. (2019)⁵ have assessed the biological water quality of Uttarakhand section of River Ganga by taking the sample from three locations, namely, Haridwar Barrage and upstream and downstream of the Jageetpur Sewage Treatment Plant. All in all 1,560 persons from 32 families and 12 taxonomic orders were recorded. They observed comparatively good biological water quality at Haridwar Barrage and upstream compared to the downstream site where there was a significant shift in the community composition due to discharge of wastewater. Following the discharge-affected area, an increase in the dominance of Chironomidae and a loss of Ephemeroptera were observed. This study would be of special relevance as it would give scientific support to the study of biological water quality in Haridwar on regional basis.

III. OBJECTIVES

3.1 Specific objectives

1. To determine different major groups and families of benthic macro-invertebrate present in the selected sites of Haridwar section of Ganga.
2. To assess the abundance, taxonomic richness, diversity, and distribution of the macro-invertebrates.
3. To measure certain physiochemical values such as temperature, pH, dissolved oxygen, BOD, conductivity and turbidity.
4. To assess water quality based on biological indicators, such as macro-invertebrates, where regional water quality scoring criteria are available for the appropriate approach, e.g., BMWP.
5. To compare the conditions (biological and physicochemical) at the sampling points⁶.

IV. MATERIALS AND METHODS

4.1 Study area

The study area is Haridwar section of River Ganga in Uttarakhand, India. Haridwar is a religious and urban hub having river usage related with bathing, tourism, urban drains and wastewater management. This section of the river offers an

⁴ Goel, A., Sharma, J., & Durgapal, N. C. (2021). Assessment of biological water quality of river Ganga in Patna (India) using benthic macro-invertebrates. *Applied Biological Research*, 23(2), 136–146. <https://doi.org/10.5958/0974-4517.2021.00019.7>

⁵ Agrawal, S., Sharma, J., & Goel, A. (2019). Bioassessment of river Ganga in Uttarakhand stretch (India) using benthic macro-invertebrates as bioindicator. *Applied Biological Research*, 21(3), 235–244. <https://doi.org/10.5958/0974-4517.2019.00030.2>

⁶ Courtwright, J. L., & Hawkins, C. P. (2024). Assessing stream biological integrity across gradients of flow permanence and hydrologic connectivity. *Freshwater Science*, 43(4). <https://doi.org/10.1086/732247>



opportunity to study the spatial variation in aquatic biological communities due to differences in the flow conditions, river bed composition, and human activities.⁷

The study design consists of sites with varying degrees of human influence. Sampling coordinates should be recorded during fieldwork to the best of accuracy.

4.2 Sampling locations

This study design has three main sampling sites.

A site of collection. Location of intended sampling site.

Sampling site	Proposed location	Purpose
Site 1	Haridwar Barrage or a suitable upstream reference location	Assess biological and physicochemical conditions at the selected reference site
Site 2	Har Ki Pauri or another accessible, heavily used river stretch	Examine conditions in an area influenced by intensive human activity
Site 3	A suitable downstream location near Jagjeetpur, selected with reference to wastewater inputs	Assess potential changes in water quality and macro-invertebrate composition

The sites are suggested for investigation. They are finally picked based on how accessible they are, how much water flows through them, how they compare to the other river, permissions, and the presence of identifiable pollution sources. The reference site should not be taken for granted to be pollution free.⁸

4.3 Sampling design

To take into consideration seasonal changes, the sampling design includes pre-monsoon, monsoon and post-monsoon. If resources are limited, at least two contrasting seasons are included in the design⁹.

At each location:

- Three or more replicate benthic samples are taken from similar habitats as part of the protocol.
- The protocol documents sampling date, time, weather, water depth, current velocity and substrate characteristics.
- Habitats sampled include cobbles, gravel, sand and submersed organic material, as appropriate.
- All sites subject to a standard sampling method and sampling effort.
- GPS data and other observations on local human activity are made.

Replicates are not independent samples unless they are sampled in such a way that the sampling design makes that interpretation possible¹⁰.

⁷ Yuan, L. L., Carlisle, D. M., Mitchell, R. M., & Pollard, A. I. (2024). Using models of local environmental conditions for biological assessment. *Freshwater Science*, 43(3), 325–339. <https://doi.org/10.1086/731770>

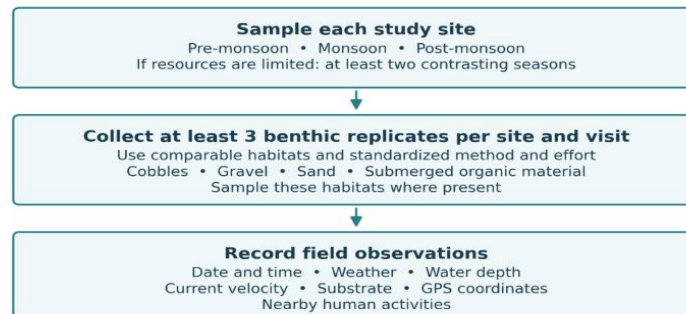
⁸ Liu, Y., et al. (2024). Comparison of different macroinvertebrates bioassessment indices in a large near-natural watershed under the context of metacommunity theory. *Ecology and Evolution*, 14(2), Article e10896. <https://doi.org/10.1002/ece3.10896>

⁹ Deciphering urban freshwater health through integrated assessment of benthic macroinvertebrate assemblage and physicochemical dynamics in artificial ponds of Prayagraj, India. (2025). *Discover Ecology*. <https://doi.org/10.1007/s44396-025-00020-x>

¹⁰ Distribution of the riverine benthic macroinvertebrate community along the Citarum cascading dam system in West Java, Indonesia. (2023). *Global Ecology and Conservation*, 46, Article e02580. <https://doi.org/10.1016/j.gecco.2023.e02580>



Proposed seasonal sampling design



Treat replicates as independent only when supported by the sampling design.

Figure 1: Proposed Seasonal Sampling Design

4.4 Collection of benthic macro-invertebrates

The sampling protocol is based on an appropriate kick net, Surber sampler or other standard benthic sampling equipment, depending on water depth, flow, and substrate.

The substrate above the net is disturbed for a fixed length and width of time in kick sampling to move the organisms into the net. Samples should be recorded separately from the different techniques required for each habitat.

The collected material is put in labeled containers and preserved in a suitable laboratory procedure. Samples are identified by site, date, replicate number and habitat type.¹¹

4.5 Identification of macro-invertebrates

Samples are sorted at appropriate magnification and organisms identified by reference to taxonomic keys and regional identification guides. Identification is at family level or genus/species level if possible¹².

The following are the major groups to be covered:

- Ephemeroptera — mayflies
- Trichoptera — caddisflies
- Plecoptera — stoneflies
- Diptera — true flies, including Chironomidae
- Coleoptera — aquatic beetles
- Hemiptera — true bugs
- Odonata — dragonflies and damselflies
- Mollusca — snails and bivalves
- Annelida — segmented worms and related groups
- Crustacea — aquatic crustaceans

The taxonomic composition is not hypothesized a priori, but derives from the specimens collected.¹³

¹¹ Munyai, L. F., et al. (2024). The drivers of benthic macroinvertebrates communities along a subtropical river system: Sediments chemistry or water quality? *Ecohydrology*, 17(5), Article e2649. <https://doi.org/10.1002/eco.2649>

¹² Linking physico-chemical parameters and macroinvertebrates for water quality assessment of Kakamega and the East Usambara montane ecosystems in Kenya. (2024). *African Journal of Ecology*, 62(2), Article e13274. <https://doi.org/10.1111/aje.13274>



4.6 Physicochemical analysis

The water sample is taken following the suitable standard method for water sampling as outlined in the proposed protocol. The parameters listed below are proposed to be measured in the field and analyzed in the laboratory¹⁴.

Parameter	Unit	Ecological significance
Water temperature	°C	Influences metabolism and dissolved oxygen
pH	pH units	Indicates acidity or alkalinity
Dissolved oxygen (DO)	mg/L	Reflects oxygen availability for aquatic organisms
Biochemical oxygen demand (BOD)	mg/L	Indicates oxygen demand associated with biodegradable material
Electrical conductivity	µS/cm	Indicates the concentration of dissolved ions
Turbidity	NTU	Indicates the scattering of light by suspended particles
Total dissolved solids (TDS)	mg/L	Represents dissolved material in water
Nitrate	mg/L	Indicates nutrient availability and possible nutrient enrichment
Phosphate	mg/L	Helps assess nutrient enrichment

Other parameters may be added if resources allow: ammonia, chemical oxygen demand, microbiological indicator.

The in situ measurement of DO, temperature, pH and conductivity is preferably made with calibrated in situ instruments. Laboratory methods are conducted in accordance with accepted procedures (Standard Methods for the Examination of Water and Wastewater).¹⁵

4.7 Statistical analysis

Data are summarized using means, standard deviations, relative abundance, taxonomic richness and diversity indices, as appropriate¹⁶.

The planned analyses are:

1. Analysis of variance or appropriate non-parametric tests to compare sites and seasons.
2. One-way analysis of variance to assess any differences among the different biological indexes. Correlation analysis to look for any association between the biological indices and the physicochemical variables.
3. use multivariate community analysis (e.g. non-metric multidimensional scaling) to compare the taxonomic composition.
4. Analysis of relationships between selected environmental parameters with biological responses using regression analysis.

The selection of statistical test is dependent on the size of the samples, assumptions on distribution, independence, and the design of the sampling. Effect size and uncertainty (where possible) is reported together with statistical significance.¹⁷

¹³ Edwards, P. M., Bedell, D., Hubler, S. L., Larson, C. A., Macneale, K. H., Mickelson, E., Prescott, C., Webb, E., & Wilhelm, J. (2024). An index of biotic integrity for macroinvertebrate stream bioassessment conducted by community scientists. *Freshwater Science*, 43(2). <https://doi.org/10.1086/730537>

¹⁴ Macroinvertebrate communities respond strongly but non-specifically to a toxicity gradient derived by effect-based methods. (2024). *Environmental Pollution*, 356, Article 124330. <https://doi.org/10.1016/j.envpol.2024.124330>

¹⁵ Jin, X., Lan, X., Sun, H., Hu, B., & Wang, B. (2024). Assessment of water quality using benthic diatom and macroinvertebrate assemblages: A case study in an East China canal. *Water Biology and Security*. <https://doi.org/10.1016/j.watbs.2023.100231>

¹⁶ Mandal, [initials and co-authors to be verified]. (2025). Study on the macroinvertebrates community, a bio-indicator of water quality in Deepor Beel (Ramsar Site), Assam. *Lakes & Reservoirs*. <https://doi.org/10.1111/lre.70009>

¹⁷ Dutta, B., & Borah, R. (2025). A study of river water quality using macroinvertebrates as bio indicator: A case study. *Agricultural Science Digest*. <https://doi.org/10.18805/ag.D-6255>



V. DISCUSSION

5.1 Ecological significance of benthic macro-invertebrates

Benthic macro-invertebrates have a significant biological perspective on freshwater quality as their community responds to environmental conditions over varying timeframes. Community composition may be a more integrative measure than a single physicochemical parameter, and may be related to the overall influence of oxygen availability, organic enrichment, habitat quality and disturbance.¹⁸

The interpretation of the study centers on relationships between changes in the number of taxa, diversity and relative abundance and the measured differences in physicochemical conditions. Repeated samples that show consistent patterns would be more convincing than isolated samples.

5.2 Relationship between macro-invertebrates and dissolved oxygen

Dissolved oxygen is an important factor governing the distribution of aquatic organisms. Many aquatic insect larvae have low oxygen demands, and some are able to withstand low oxygen levels¹⁹.

Combined data from lower DO and fewer sensitive taxa and higher relative abundance of pollution-tolerant taxa may indicate environmental stress at the sampling site. However, the relationship should only be assessed based on real measurements and taking into account habitat conditions.

5.3 Organic enrichment and community structure

Any organic matter that enters a river can cause a stimulation of microbial decomposition, which raises oxygen demand. If so, it can change the nature of benthic communities and promote oxygen-tolerant species.

Agrawal et al. (2019) give an appropriate example in the regional study. This study by the authors found a shift in the macro-invertebrate community composition was related to a reduction of water quality in the Ganga in the Uttarakund area.²⁰

The study investigates if there are corresponding trends at the selected sites. But it is important to note that any similarities with previous research are used not as a comparator, but rather as a basis of comparison; they are not indicators of the presence of identical conditions today.

5.4 Influence of human activities in Haridwar

Intense human use occurs in the Haridwar stretch, especially in the areas of religious bathing and at urban sites. Wastewater inputs, solid waste disposal, physical disturbance of riverbed habitats, and changes due to river regulation are potential pressures²¹.

These stresses can be received by aquatic communities in a variety of ways. Factors such as changes in substrate types may affect the type or number of organisms capable of existing at a site, and organic pollution can affect oxygen levels

¹⁸ Sithole, H., Motitsoe, S. N., Mutshekwa, T., et al. (2025). Unravelling the long-term river health status of Kruger National Park Rivers using macroinvertebrate-based monitoring. *Environmental Monitoring and Assessment*, 197, Article 914. <https://doi.org/10.1007/s10661-025-14343-5>

¹⁹ Nautiyal, P., & Dwivedi, A. C. (2025). Benthic macroinvertebrates in bioassessment of Ramganga River, a Himalaya tributary of the Ganga basin: River health assessment in Himalaya. *Aquatic Ecosystem Health & Management*, 28(4).

²⁰ Mureithi, P. W., Aine, A., Basooma, R., Namumbya, J., Nansumbi, F., Yegon, M. J., Meimberg, H., & Graf, W. (2025). Advancements in macroinvertebrate-based river bioassessment research in the Afrotropical region: Review and steps towards a regional framework. *Environmental Monitoring and Assessment*, 197, Article 935. <https://doi.org/10.1007/s10661-025-14272-3>

²¹ Rapid assessment implementation in the development of biocriteria and organic enrichment evaluation in the Citarum River, Indonesia. (2024). *International Journal of Environmental Studies*, 871–890. <https://doi.org/10.1080/00207233.2024.2409044>



and food availability. These effects must be separated and this can only be done in conjunction with biological and physicochemical measurements and habitat observations.

5.5 Comparison with conventional water-quality assessment

The Physicochemical analysis gives quantitative details on particular characteristics of water at the time of the analysis. Biological assessment will supplement these observations, providing an indication of the response of aquatic organisms to environmental conditions.

These methods can be combined to enhance the assessment of river health. Biological indices are not replacements for chemical tests, however, and they can't definitively prove the presence of a specific toxic chemical or pathogen.²²

5.6 Implications for river management

The assessment proposed in this document may provide information that will help in river management, showing areas where biological communities vary significantly and areas in need of further investigation²³.

Some potential management options are:

- Increase monitoring of wastewater treatment and discharge sites.
- Avoidance of direct discharge of untreated sewage and solid waste.
- Conserving heterogenous river bed habitat and riparian areas.
- Repeated biological and physicochemical evaluations.
- Incorporating macro-invertebrate monitoring into regular river-health programs.

These recommendations are ranked based on the evidence collected during the study and not on any assumptions about the condition of sites.

VI. LIMITATIONS OF THE STUDY

There are some limitations that need to be taken into account when interpreting the findings.

First is that natural environmental factors such as current velocity, type of substrate, depth, temperature and seasonal life cycles affect macro-invertebrate communities. Habitat variation may thus contribute to the differences among sites, as well as pollution.

Second, because of the equipment, skills, and condition of specimens collected, taxonomic identification might also be restricted. Family level identification can be helpful but hybridization can occur across species which may not have similar tolerance to pollution²⁴.

Thirdly, a short-term study may not reflect a yearly or long-term trend. Multiple sampling within seasons and years increases the accuracy of comparisons.

Fourth, biological indices are not readily transferable from one region to another without validation for local ecological conditions.

²² Rapid assessment implementation in the development of biocriteria and organic enrichment evaluation in the Citarum River, Indonesia. (2024). International Journal of Environmental Studies, 871–890. <https://doi.org/10.1080/00207233.2024.2409044>

²³ Taxonomic accuracy and complementarity between bulk and eDNA metabarcoding provides an alternative to morphology for biological assessment of freshwater macroinvertebrates. (2024). Science of the Total Environment, 935, Article 173243. <https://doi.org/10.1016/j.scitotenv.2024.173243>

²⁴ Welti, E. A. R., Bowler, D. E., Sinclair, J. S., Altermatt, F., Álvarez-Cabria, M., Amatulli, G., Angeler, D. G., Archambaud, G., Arrate Jorrín, I., Azpiroz, I., Baker, N. J., Bañares, I., Barquín Ortiz, J., Bonacina, N., & others. (2024). Time series of freshwater macroinvertebrate abundances and site characteristics of European streams and rivers. Scientific Data, 11. <https://doi.org/10.1038/s41597-024-03445-3>



Lastly, pollution sources and causal relationships cannot be determined from the differences in macro-invertebrate communities in the proposed study. Other chemical analysis, monitoring of discharges, and appropriate statistical designs may be required.²⁵

VII. CONCLUSION

The benthic macro-invertebrate can be used as a good tool to understand the biological status of River Ganga at Haridwar. They are useful for detecting ecological trends as water quality and habitat conditions change because of their taxonomic composition, abundance and diversity. Biological assessment provides a more holistic view of river health than physicochemical assessment alone.

The study design involves the use of standard sampling, taxonomic identification, diversity indices and appropriate biological monitoring procedures to assess selected locations from Haridwar stretch. Its primary value will be to determine if patterns in the biology are related to patterns in the measured environmental variables and if patterns vary by season or location.

The relevance of macro-invertebrate based assessment is observed from previous studies conducted in Uttarakhand section of Ganga, which show that macro-invertebrates are suitable bio-indicator for detecting biological changes due to wastewater related impacts.

New observations, specific to the site, could be used as a building block for the proposed investigation.

Finally, the degree of reliability in the conclusions will be dependent on a systematic sampling of the field, sound taxonomic identification, appropriate biological scoring means and careful examination of the data collected. The results of the study may help with the management of ecological monitoring, determination of areas needing further research, and the creation of science-based river conservation efforts.

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²⁵ Kumar, K., & Dobriyal, A. K. (2026). Nature's indicators at work: Using benthic macroinvertebrates for biomonitoring of an unexplored Rawasan stream, Central Himalaya, India. *H2Open Journal*, 9(4), Article 100054. <https://doi.org/10.1016/j.htopen.2026.100054>



7. Liu, Y., et al. (2024). Comparison of different macroinvertebrates bioassessment indices in a large near-natural watershed under the context of metacommunity theory. *Ecology and Evolution*, 14(2), Article e10896. <https://doi.org/10.1002/ece3.10896>
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