Vol. 33: 1–11, 2024
https://doi.org/10.3354/ab00763

AQUATIC BIOLOGY
Aquat Biol

Published February 1

Macroinvertebrate community composition and river health assessment in plateau rivers of Guizhou Province, China

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ABSTRACT: Plateau rivers are considered regional water resource depots, hydropower energy bases, cradles of aquatic dispersal, and barriers to invasive alien species. In this study, 20 major plateau rivers from Guizhou Province, China, were studied to (1) investigate the composition, functional feeding group distribution, and diversity of macroinvertebrates; and (2) assess the ecosystem health of the rivers using the macroinvertebrate Family Biotic Index. Among the macroinvertebrate species, the dammed river sections primarily contained *Corbicula fluminea* and *C. nitens* from the Lamellibranchia, the urban river sections harbored *Bellamya aeruginosa* and *Semisulcospira cancellata* from the Gastropoda, and the reference river sections contained sensitive taxa including mayfly *Ecdyonurus yoshidae* and caddisfly *Stenopsyche tlenmushanensis*. Among the major plateau rivers in Guizhou, urban river sections exhibited the highest density of macrobenthic organisms. The Shannon-Wiener index was lowest in dammed sections, followed by urban sections, while reference sections exhibited the highest diversity. As for functional feeding groups, the density of filter feeders was significantly higher than that of other groups. In contrast, the density of gatherer-collectors and the shredders was relatively low. Assessment of the aquatic ecosystem health in Guizhou Plateau rivers showed that dammed sections were primarily in an unhealthy state, urban sections mainly fell into the sub-healthy category, and reference sections had a relatively good health status. The results from this study provide baseline data that is useful for water resources management, hydropower energy utilization, and ecological and environmental protection of the plateau rivers.

KEY WORDS: Plateau rivers · Biodiversity · Terraced reservoirs · Family biotic index · Functional feeding taxa

1. INTRODUCTION

Rivers are important water sources for human life, transportation, irrigation, aquaculture, and tourism (Wu et al. 2021). Consequently, humans have undertaken extensive development of rivers, with the main components including the construction of dams and urbanization (Chen et al. 2020). Since the Industrial Revolution, over 70 000 dams have been built worldwide for flood control, navigation, and electricity generation (Maavara et al. 2015). While dam construction provides clean energy for humans and safeguards them from the threat of floods (Moran et al. 2018), it also poses multiple ecological problems such as blocking fish migration routes, eutrophication, and greenhouse gas emissions (Su et al. 2023). Urbaniza-

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tion, while promoting socio-economic development, also poses a serious threat to the health of river ecosystems within watersheds (Ren et al. 2022), which leads to deteriorating water quality, disruption of hydrological patterns, and a sharp decline in biodiversity in rivers.

The abundant water resources of plateau rivers, coupled with low levels of human disturbance, make them crucial water sources and hydropower energy bases within their watersheds (Lutz et al. 2014, Tang et al. 2021, Merovich et al. 2022). They play a significant role in global energy security, energy conservation, emissions reduction, and biodiversity conservation (van Riemsdijk et al. 2017, Wang et al. 2022). However, these rivers are sensitive to human activities such as river damming and anthropogenic disturbances, and the current status and future evolution of water ecosystems in the rivers need further research. Particularly, it is important to understand the changing patterns of water ecosystems in plateau rivers in the context of rapid changes in the global water cycle and ecosystems. The diversity, richness, and distribution of aquatic organisms such as fish, macroinvertebrates, and phytoplankton can be used to evaluate the health of river ecosystems (Winemiller et al. 2016, Moran et al. 2018, Wu et al. 2023). However, anthropogenic activities are affecting the health of aquatic ecosystems. Therefore, analyzing the impact of natural and anthropogenic stress on the structure, spatial distribution, and function of aquatic organisms is critical to providing targeted guidance for river water conservation and management of aquatic ecosystems.

Macroinvertebrates live on the bottom of water bodies for most of their life history and are important to aquatic biodiversity and ecosystems (Gräfnings et al. 2023, Le et al. 2023). They are largely sedentary as larvae and are therefore excellent indicators of local environmental conditions in riverine ecosystems (Cox et al. 2019, Khatri et al. 2020, Su et al. 2021). In addition, macroinvertebrate taxonomic and functional diversity are key indicators of the ecosystem health of rivers because they typically have longitudinal distribution characteristics and can easily be impacted by the water level and geomorphology of rivers (Vaughan & Gotelli 2019, Khatri et al. 2021, 2023). Indeed, several previous studies have used macroinvertebrates as indicator species for river biodiversity and ecosystem health (Liu et al. 2019, Zhang et al. 2021, Calabria et al. 2022). A typical method is the Index of Biotic Integrity (IBI) (Chen et al. 2014, Hilburn et al. 2023), which is constructed by selecting biological composition, structure, and functional parameters sensitive to environmental stressors. Due to factors such as topography, logistics, and weather conditions, conducting on-site field surveys in high-altitude rivers can be challenging (Zhang et al. 2022), making it difficult to construct an accurate IBI system. The Family Biotic Index (FBI) method assesses river health based on the average tolerance values of all taxonomic groups in the samples. It can reflect the impact of human disturbances on river health and offers the advantages of requiring less data and providing a quicker assessment. It has already been utilized to assess the health of high-altitude rivers with sampling difficulties, such as the Yellow River source region (Liu et al. 2019).

Guizhou Province covers a total area of 176 200 km^2 and is located in the inland southwestern region of China, with an average altitude of about 1100 m above sea level (a.s.l.). The region is situated in the overlapping area of the upper reaches of the Yangtze and Pearl river systems where it serves as a crucial ecological barrier. The main objectives of this study were to (1) investigate the composition, functional feeding group distribution, and diversity of macroinvertebrates in plateau rivers; and (2) assess the ecosystem health of the plateau rivers using the macroinvertebrate FBI.

2. MATERIALS AND METHODS

2.1. Study area

Guizhou Province is located in the hinterland of southwest China (24° 37′ to 29° 13′ N, 103° 36′ to 109° 35′ E) and is the transportation hub of the region and constitutes an integral part of the Yangtze River Economic Belt. The landscape of the province belongs to the mountainous plateau of southwestern China, with high terrain in the west and low in the east, and an average altitude of about 1100 m a.s.l. To address the key issues of declining health and biodiversity of aquatic ecosystems in the Yangtze River basin, 20 representative main river channels were selected for sampling. A total of 58 monitoring sections were deployed across reference, dammed, and urban sections of the rivers (Fig. 1). The selected 20 typical rivers all had lengths exceeding 100 km, and they flowed through diverse habitats, encompassing natural, dammed, and urban environments, and sometimes a combination of 2 of these types. The monitoring points along the same river were spaced more than 10 km apart to reduce mutual interference between points and to avoid pseudo-replication.

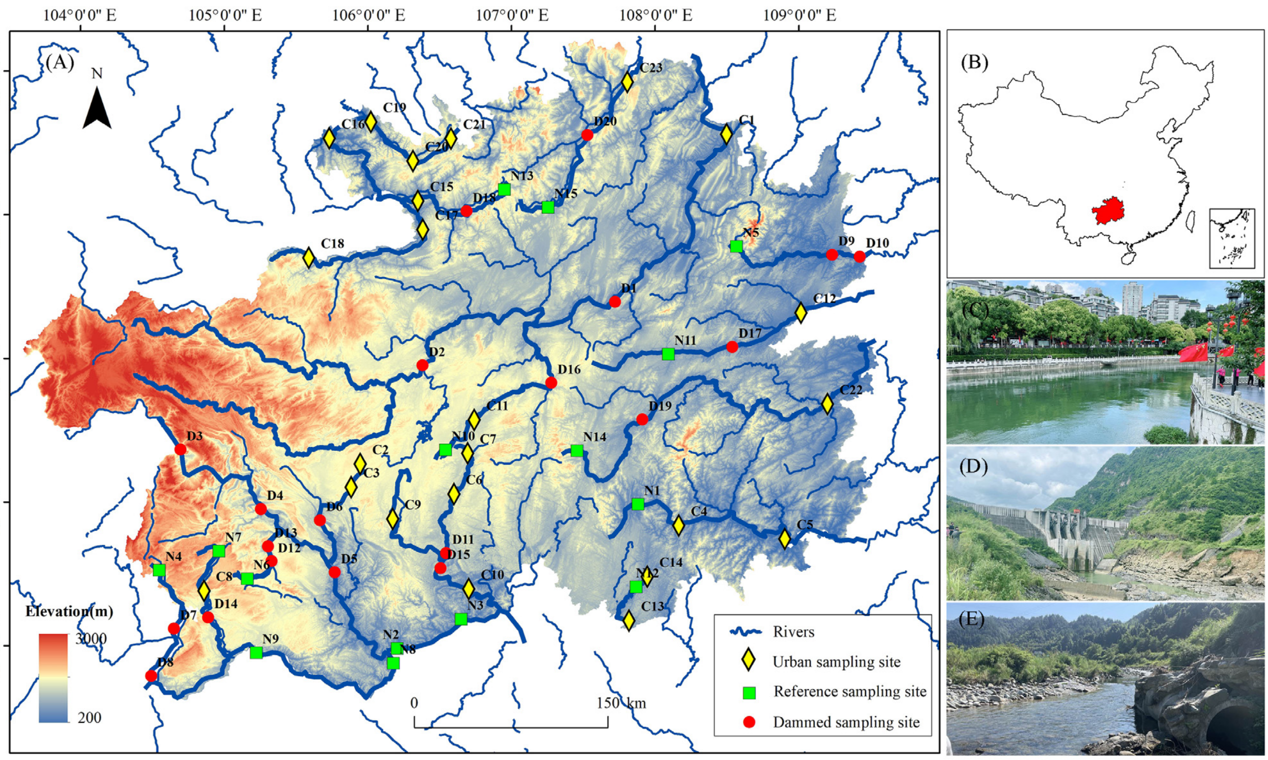

Fig. 1. Study area and sampling sites: dammed (n = 20), urban (n = 23), and reference (n = 15). (A) Sampling sites in plateau rivers. The elevation of each point is shown in Table 2. (B) Guizhou Province in China. (C) Urban sampling site. (D) Dammed sampling site. (E) Reference sampling site

In this study, a reference reach was defined as the headwater region of a river with little to no human disturbance. A dammed reach (below-dam reach) was defined as a 1 km segment downstream from the dam, where the aquatic habitat was significantly affected by dam construction. A river segment was designated as urban reach if it was situated near towns or villages with a population of over 1000 residents, indicating substantial human activity impacts on the aquatic habitat. The selection of monitoring sections and sampling sites was determined through a combination of sources, including the Guizhou Statistical Yearbook, Guizhou Water Resources Bulletin data on population distribution and dam locations, field surveys, and Google Earth satellite imagery.

2.2. Sample collection

A survey of macroinvertebrates was conducted from July to August of 2021. Out of 58 monitoring sections, 15 were selected from reference (N1 to N15), 20 from dammed (D1 to D20), and 23 from urban (C1 to C23) sections of the rivers. Using the technical guidelines for biodiversity monitoring of freshwater benthic macroinvertebrates provided by the Ministry of Ecology and Environment of the People's Republic of China (2014), and based on the morphology, width, and substrate type of the river, a 500 µm mesh D-shaped net was employed. At each sampling point, we collected 6 subsamples from the water-accessible area within 100 m upstream and downstream. The sampling area for each subsample point was 0.3 m^2. We combined samples from 6 subsample points into 1 composite sample. Hence, total sampling area for each sampling point was 1.8 m^2. The collected macroinvertebrate samples were sieved through a 500 µm steel mesh after collection to remove impurities, and then placed into 500 ml specimen bottles. The samples were preserved by adding a 10% formalin solution. In the laboratory, the benthic animals were identified and analyzed (Yi et al. 2018).

The samples were handpicked and placed in an enamel dish. When possible, all specimens were identified to the lowest taxon (genus or species level): oligochaetes were identified to the class level and chironomids were identified to the family level. The total number of organisms detected at each sampling site was used to calculate the macroinvertebrate density (individuals [ind.] m^{-2}) (Yan et al. 2020). Identified macroinvertebrates were classified into 5 categories based on benthic feeding habits: shredders (SH), gatherer-collectors (CO), scrapers (SC), predators (PR), and filter-collectors (FS) (Tachet et al. 2002, Poff et al. 2006).

2.3. Data analysis

2.3.1. Biological index calculation. The Shannon-Wiener index (H') was calculated to determine the species diversity of macroinvertebrates in the plateau rivers (Ludwig & Reynolds 1988). The Ephemeroptera, Plecoptera, and Trichoptera (EPT) genus richness (E) was calculated to reflect the impact of anthropogenic disturbance on the river ecosystem (Kitchin 2005). The FBI was calculated to assess the health of the river ecosystem (Musonge et al. 2019, Kumari & Maiti 2020). The tolerance values at the family level were calculated following the technical guidelines for monitoring and evaluation of river water ecological environment quality (Ministry of Ecology and Environment of the People's Republic of China 2021):

$$H = -\sum_{i=1}^{s} (n_i/N)\log_2(n_i/N) \quad (1)$$

$$E = S_E + S_P + S_T \quad (2)$$

$$FBI = \sum_{i=1}^{n} \frac{N_i t_i}{N} \quad (3)$$

where n_i is the total number of individuals of species i, N is the total number of individuals of all species, S is the total number of species, S_E is the number of Ephemeroptera, S_P is the number of Plecoptera, S_T is the number of Trichoptera, N_i is the total number of individuals of family i, and t_i is the tolerance value at the family level.

2.3.2. Statistical analysis. Two biodiversity indices, the Shannon-Wiener index and EPT genus richness, were investigated. The Kruskal-Wallis test was performed to identify significant differences between and within groups of samples. Non-metric multidimensional scaling (NMDS) based on Bray-Curtis similarity was used to investigate the variations in the macroinvertebrate community. The analysis of similarities (ANOSIM) (for 999 permutations of the data) test was employed to assess the significant differences in community composition between the 3 habitats (reference, urban, and dammed sections) (Merovich et al. 2022).

All statistical analyses were conducted in the R statistical environment Version 4.0.3 (R Core Team 2020). NMDS and ANOSIM were performed with the vegan package (Oksanen et al. 2019). The distribution of macroinvertebrate density was spatially represented using a Geographic Information System (GIS) software platform. The spatial distribution method employed was the inverse distance weighting (IDW) method (Su et al. 2023). IDW is a common spatial interpolation method. It uses a set of known sample point values and the weights of the remaining points in the study area to determine the values of each point. The weights are inversely proportional to the Euclidean distance in spatial coordinates between the known and unknown points.

2.3.3. Health evaluation. The macroinvertebrate family-level pollution tolerance values were determined using the technical guidelines for monitoring and evaluation of river water ecological environment quality (Ministry of Ecology and Environment of the People's Republic of China 2021). The ecosystem health of the rivers was evaluated using the FBI, and the evaluation criteria are shown in Table 1.

3. RESULTS

3.1. Distribution of macroinvertebrate communities

A total of 1803 benthic animals belonging to 115 taxonomic units, 4 phyla, 8 orders, and 56 families were collected from the plateau rivers. The composition of the major taxa (Fig. 2A) showed that the main constituents of macrobenthic organisms in the Guizhou Plateau rivers were Gastropoda and Lamellibranchia. Among them, dominant species within the Gastropoda included *Radix auricularia* and *Semisulcospira cancellata*, while within Lamellibranchia, *Corbicula fluminea* and *Limnoperne lacustris* were dominant. These 2 groups accounted for 61.13% of the total abundance, depicting an in-stream habitat. Dammed sections exhibited the highest diversity of

Table 1. Criteria for river health assessment using the Family Biotic Index

Condition	Natural	Healthy	Sub-healthy	Unhealthy	Morbid
Tolerance value	[0.00, 3.75]	[3.75, 5.00]	[5.00, 5.75]	[5.75, 7.25]	[7.25, 10.00]

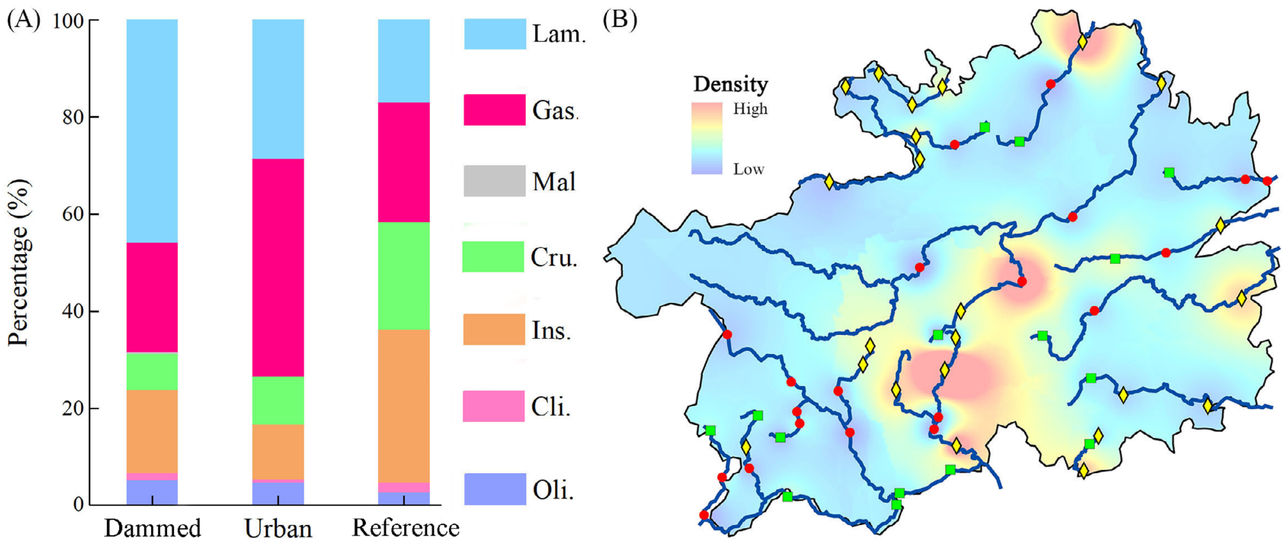

Fig. 2. Distribution of macroinvertebrate major taxa. (A) Class composition of macroinvertebrates in each river section: dammed (n = 20), urban (n = 23), and reference (n = 15). (B) Spatial distribution of macroinvertebrate density. Lam.: Lamellibranchia; Gas.: Gastropoda; Mal.: Malacostraca; Cru.: Crustacea; Ins.: Insecta; Cli.: Clitellata; Oli.: Oligochaeta. See key in Fig. 1 for sampling sites

Lamellibranchia, comprising 45.85% of the total taxonomic units, urban sections had the highest diversity of Gastropoda, constituting 44.89% of the total taxonomic units, and reference sections had the highest diversity of Insecta, comprising 31.48% of the total taxonomic units.

The spatial interpolation of macrobenthic organism density in the Guizhou Plateau rivers (Fig. 2B) revealed that the average density was 68.7 ind. m^{-2} in dammed sections, 170.1 ind. m^{-2} in urban sections, and 92.8 ind. m^{-2} in reference sections. Among the major plateau rivers in Guizhou, urban river sections exhibited the highest density of macrobenthic organisms (H' = 10.59, p = 0.005).

3.2. Composition of macroinvertebrate functional feeding taxa

In the major plateau rivers of Guizhou, there were 4 functional feeding groups of macrobenthic organisms, including gatherer-collectors (CO), scrapers

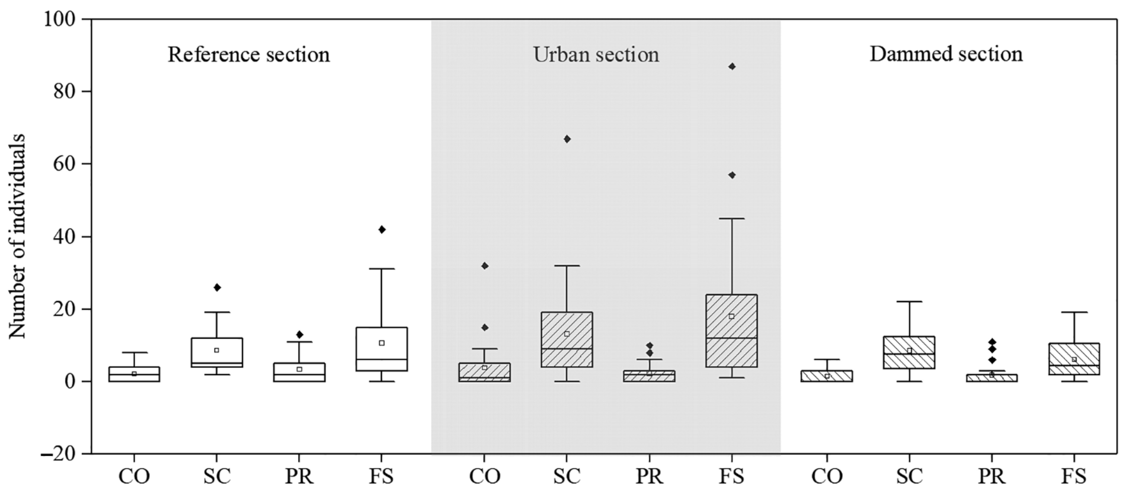

Fig. 3. Composition of macroinvertebrate functional feeding groups: dammed (n = 20), urban (n = 23), and reference (n = 15). CO: gatherer-collectors; SC: scrapers; PR: predators; FS: filter-collectors. Boxes represent the interquartile range (IQR) of the number of species in each functional group. The line in each box represents the median, and the upper and lower whiskers represent 1.5 × IQR. The hollow points indicate means and the solid points indicate outliers

(SC), predators (PR), and filter-collectors (FS) (Fig. 3). Across all monitoring points, the mean levels of SC and FS were higher than those of CO and PR, and CO and PR exhibited less fluctuation compared to SC and FS. The mean levels of all 4 functional feeding groups were lowest in the dammed sections. The highest mean levels of CO, SC, and FS occurred in the urban sections, while the highest mean level of PR occurred in the reference sections. Within the dammed sections, SC had the highest mean and maximum values, indicating its dominance in these areas, while FS dominated in urban and reference sections.

3.3. Macroinvertebrate biodiversity

EPT organisms, which include the larvae of various aquatic insects, inhabit clear and clean water bodies. They cannot survive in the presence of water pollution, and due to their large size and limited mobility, they are particularly suitable for water quality monitoring and assessment. In the Guizhou Plateau rivers, the reference sections had the highest EPT index, while the dammed sections had the lowest (H' = 13.92, $p < 0.005$) (Fig. 4). The Shannon-Wiener index primarily focuses on the number of species in locally uniform habitats and can characterize the complexity of a community. The Shannon-Wiener index was lowest in the dammed sections, followed by the urban sections, while the reference sections exhibited the highest diversity (H' = 11.47, $p < 0.005$) (Fig. 4).

3.4. River Biotic Index health assessment

The overall health status of rivers in the Guizhou Plateau was sub-healthy (Fig. 5). Among all monitor-

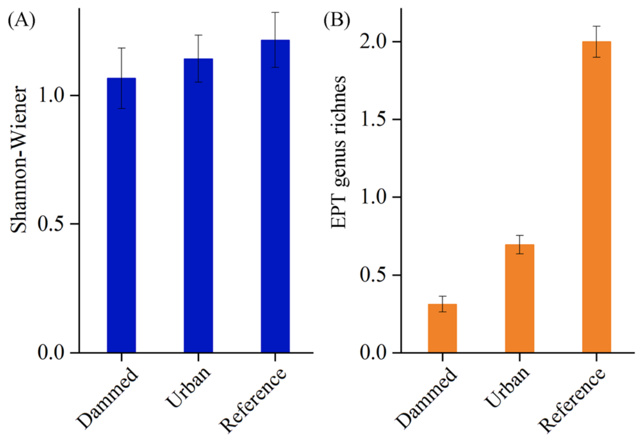

Fig. 4. Macroinvertebrate biodiversity in each river section: dammed (n = 20), urban (n = 23), and reference (n = 15). (A) Shannon-Wiener index. (B) Ephemeroptera, Plecoptera, and Trichoptera (EPT) genus richness

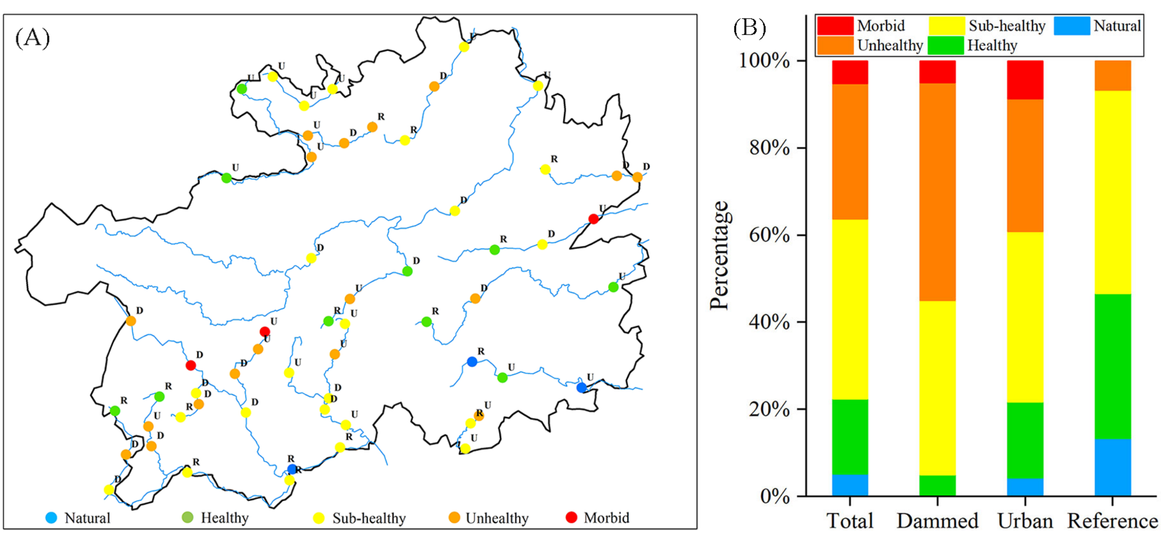

Fig. 5. Assessment of aquatic ecosystem health in Guizhou Plateau rivers: dammed (n = 20), urban (n = 23), and reference (n = 15). (A) Health status in each river section. R: reference sampling site; U: urban sampling site; D: dammed sampling site. (B) Proportion of health status in each river section. Natural: Rivers are in a natural state without any disturbance; Healthy: Rivers exhibit certain deficiencies in ecology integrity and biodiversity. Daily management and maintenance should be strengthened, and continuous efforts should be made to enhance the health of rivers. Sub-healthy: Increased efforts are needed for daily maintenance and supervision of rivers. Timely measures should be taken to address and rectify local deficiencies, eliminating potential threats to health. Unhealthy: Comprehensive measures are required for the restoration and improvement of rivers and lakes. This involves enhancing the overall appearance and ecological aspects of the water environment to elevate the health of rivers. Morbid: Rivers have suffered severe damage, necessitating fundamental measures to reshape the form and habitat of rivers and lakes

ing points, the largest proportion, accounting for 41.37%, fell into the sub-healthy category. Healthy points made up only 17.24% of the total, indicating the need for significant improvement in river health. There were significant differences in health status between dammed sections, urban sections, and reference sections. Dammed sections were primarily in an unhealthy state, with no points categorized as natural state and 50.00% of monitoring points classified as unhealthy. Urban sections mainly fell into the sub-healthy category, constituting 39.13% of monitoring points. Reference sections had a better health status, with no morbid monitoring points, and natural and healthy points together making up 46.66% of the total.

4. DISCUSSION

4.1. Impact of anthropogenic disturbance on the benthic community structure in plateau rivers

The survey results on the distribution of macroinvertebrates in Guizhou Plateau rivers revealed that these organisms were primarily composed of Gastropoda and Lamellibranchia, indicating an in-stream habitat. Among the different river sections, the reference sections exhibited the highest EPT index, followed by the urban sections, while the dammed sections had the lowest EPT index. The most significant EPT species included the mayfly *Ecdyonurus yoshidae* and the caddisfly *Stenopsyche tlenmushanensis*. The trend in the diversity of large benthic organisms aligned with the EPT index. Regarding the functional feeding groups of macroinvertebrates, SC dominated in dammed sections, while FS prevailed in urban and reference sections. NMDS results for the macroinvertebrate species (Fig. 6) show that points in dammed sections were mainly distributed in the upper left corner, reference section points were primarily in the lower right corner, and urban section points overlapped with points from both habitats. ANOSIM results ($R = 0.339$, $p < 0.05$) indicated significant differences between the 3 groups, highlighting the impact of anthropogenic disturbance on the variation of macroinvertebrate communities.

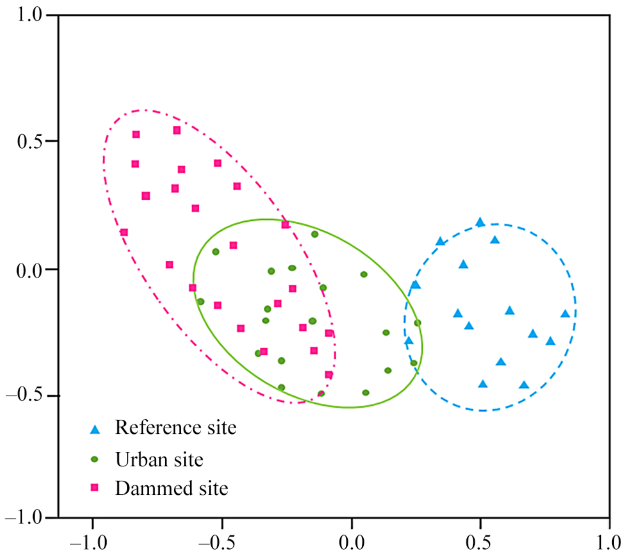

Fig. 6. Non-metric multidimensional scaling ordinations (NMDS) of benthic macroinvertebrate assemblages, stress = 0.203. Dammed (n = 20), urban (n = 23), and reference (n = 15)

Water turbidity was 16.4 ± 1.1 nephelometer turbidity units (NTU) in the dammed section, 53.3 ± 5.2 NTU in the urban section, and 39.5 ± 2.1 NTU in the reference section (Fig. 7). Most of the reservoirs built on Guizhou's rivers are cascaded reservoirs, so the below-dam reach becomes a stretch above the next dam. Thus, the dam construction likely transformed the river from a flowing to a still habitat (Chen et al. 2020), and sediment and nutrients became deposited on the bottom (Liu et al. 2012), creating a suitable habitat for the Lamellibranchia. *Corbicula fluminea* are submerged benthic animals that can survive harsher environmental conditions. They spend most of their life under the sediment, and feed on organic debris, bacteria, decaying debris, and plankton. In the dammed sections, damming has reduced the water flow, increased the water level and nutrients, and reduced the water quality compared to the reference sections of the rivers (Akyildiz & Duran 2021). The reach is suitable for macroinvertebrates that prefer static water, and are not sensitive to silt and low dis-

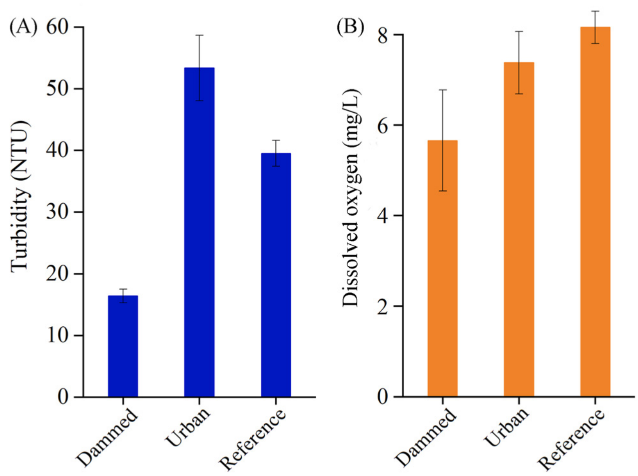

Fig. 7. (A) Turbidity and (B) dissolved oxygen concentration in each river section: dammed (n = 20), urban (n = 23), and reference (n = 15)

solved oxygen (Chen et al. 2022). The common benthic groups found in the dammed sections included *Limnodrilus* (Oligochaeta), Chironomidae (Insecta), and *C. fluminea* (Lamellibranchia). *Limnodrilus* and Chironomidae were rare in the dammed river sections because dam construction to generate electricity disturbs the sediment, negatively impacting them. However, *C. fluminea* and others were less affected because they are burrow diggers and live under the sediment.

The macroinvertebrates in urban river sections primarily comprised Gastropoda (e.g. *Bellamya aeruginosa* and *Semisulcospira cancellata*). The urban river sections are characterized by seasonal changes in water levels, landscape restoration, high water cover, intense human activity, and high water pollution (Stranko et al. 2012). Gastropoda feed on small plants and animal debris, rely on oxygen in the water for respiration through gills, are less sensitive to water pollution, and can survive in highly polluted areas. The shallow water, seasonally fluctuating water level (which provides sufficient dissolved oxygen for aquatic organisms), aquatic plants, and abundant plant and animal debris provide a suitable living environment for Gastropoda in the urban rivers.

The macroinvertebrates of the reference river sections primarily comprised taxa from the order Insecta, such as Ephemeroptera, Plecoptera, and Trichoptera (EPT), which are sensitive to water pollution. The reference reaches of the Guizhou Plateau rivers are located in high mountain valleys, far from urban areas, and less disturbed by humans, and can therefore maintain a good natural state (Zhou et al. 2019, 2022). These reaches have good water quality, a riverbed substrate dominated by boulders and cobbles, a high flow velocity, and diverse habitat types supporting EPT insects.

Guizhou Plateau rivers have significant gradients, with survey points ranging in elevation from a high of 1508.5 m to a low of 176 m (Table 2). In most sections of these rivers, the flow velocity is relatively high, and the banks are rich in vegetation, providing a plentiful supply of organic matter for aquatic and terrestrial ecosystems (Wu et al. 2015). The FS mainly rely on the action of water flow to obtain food. The shallow and fast-flowing plateau rivers in Guizhou provide suitable filter-feeding flow habitats for FS, making them the dominant functional group (Fierro et al. 2015). In contrast, CO feed on particulate matter and organic debris. However, high flow regimes make the deposition of such materials less likely, putting CO at a disadvantage. The proportion of SC in the dammed sections was higher than that of FS, indicating an increased primary productivity in the region. At the same time, the vertical transport capacity is lower. Increased primary productivity and reduced vertical transport may increase the nutrients and pollutants in the river systems, degrading the health of the aquatic ecosystem (Buss et al. 2004, Graça et al. 2004).

4.2. Health evaluation of plateau river ecosystems

The health assessment of the river water ecosystem using the FBI showed that the rivers in the study area were in a sub-healthy state. The landscape of Guizhou is part of the mountainous plateau in southwestern China, with deep and narrow river valleys, large water volumes, and many dams, including the famous Gupitan Arch Dam on the Wu River (Wu et al. 2022). Although dam construction is important for energy

Table 2. Elevation of monitoring sites: dammed (n = 20), urban (n = 23), and reference (n = 15)

Site	Elevation (m)	Site	Elevation (m)	Site	Elevation (m)	Site	Elevation (m)
C1	297.9	C15	396.1	N6	1286.1	D5	368.7
C2	1385.4	C16	231.4	N7	1379.8	D6	641.8
C3	1129.3	C17	400.9	N8	345.0	D7	1265.5
C4	302.3	C18	611.5	N9	447.7	D8	809.5
C5	176.0	C19	230.4	N10	1245.3	D9	238.6
C6	950.9	C20	680.1	N11	527.0	D10	217.1
C7	1034.3	C21	1006.1	N12	417.9	D11	607.6
C8	1100.8	C22	295.4	N13	1034.4	D12	887.8
C9	1079.9	C23	415.1	N14	988.0	D13	725.2
C10	370.2	N1	389.2	N15	668.0	D14	900.1
C11	1062.2	N2	344.7	D1	676.0	D15	505.7
C12	326.7	N3	418.3	D2	971.4	D16	760.2
C13	346.0	N4	1508.5	D3	920.3	D17	436.2
C14	458.6	N5	630.0	D4	608.8	D18	550.2
D19	577.4	D20	546.1				

security and the socio-economic development of the region, their operation has changed the hydrological processes in the rivers, transforming them into hydrostatic habitats. Reduced water flow increases sediment and nutrient deposition in rivers, causing a deterioration of the water quality. In addition, the construction of dams disrupts the longitudinal connectivity of rivers and homogenizes the riverbed substrate habitats in the impoundment area. The ecological effects of these changes in urban river sections have been highlighted by Grumbine & Xu (2011). Also, the river—lake phase separation has changed the flow pattern of the natural river, reducing the length of the natural river phase, and forming a deep and slow-flowing lake reservoir before the dam. The difference in habitats between the river and lake phases has caused rapid changes in water temperature, oxygen concentration, flow velocity, and substrate in the river water column (Li et al. 2015, Pan et al. 2015), affecting benthic animal richness and diversity. Particularly harsh environmental conditions favor only a few groups, including mosquitoes, that tolerate low oxygen conditions. The dissolved oxygen (DO) concentration was 5.66 ± 1.12 mg l^{-1} in the dammed section, 7.38 ± 0.69 mg l^{-1} in the urban section, and 8.16 ± 0.36 mg l^{-1} in the reference section (Fig. 7).

The urban river sections run through the densely populated cities of Guiyang and Chishui and are strongly influenced by human activity. Pollutants, such as domestic sewage, wastewater from livestock farming, and residue from pesticides and fertilizer, are directly or indirectly transported into the river, resulting in higher nutrient concentrations in the water body and certain impacts on the water ecosystem. The reference river sections are located in a high mountain valley, far from urban areas, with reduced human interference, and the rivers have maintained a good natural state. However, the impact of tourism in recent years, including canyon rafting and other entertainment projects, has put pressure on the rivers, reducing the health of the water ecosystem.

5. CONCLUSIONS

Plateau rivers are regional water resource reserves, hydropower energy bases, cradles of hydro-biological dispersal, and barriers to invasive alien species, and they are important for regional water security. In this study, the macroinvertebrates of 20 major plateau rivers in Guizhou Province was investigated to (1) determine the spatial distribution of macroinvertebrates, and (2) evaluate the effects of dam construction and human activities on the benthic macroinvertebrate community structure. The results showed that macroinvertebrates in the dammed river sections were primarily *Corbicula fluminea* and *C. nitens*. The macroinvertebrates of the urban river sections consisted of Gastropoda (e.g. *Bellamya aeruginosa* and *Semisulcospira cancellata*). In contrast, reference sections of the rivers contained disturbance- and pollution-sensitive taxa from the Insecta, such as EPT. The FBI showed that dammed sections were primarily in an unhealthy state, urban sections mainly fell into the sub-healthy category, and reference sections had a relatively good health status.

The biodiversity of plateau rivers is rich, but their ability to withstand external disturbances and to self-repair is low. Despite the abundance of water resources, these rivers are heavily impacted due to high levels of development. Specific ecological conservation measures need to be implemented based on different habitat conditions. Reference river segments, characterized by low disturbance and development, exhibit high benthic macroinvertebrate density and diversity, indicating better ecological health. Ecological restoration efforts in these areas should focus on natural recovery, addressing invasive species, and establishing appropriate protected areas. In contrast, dammed areas and urban river segments experience significant human disturbance, leading to increased health risks. Ecological restoration in these regions should center around artificial ecological engineering, controlling pollution sources entering the rivers, restoring river connectivity, and rehabilitating biological habitats.

Most upland rivers are located in high mountain valleys; therefore, there were some logistical difficulties during the sampling. The intense pressure on these rivers from hydro-energy developments and significant human activity was apparent, and the disturbance has placed them in a fragile condition. Therefore, future research should (1) increase the sampling frequency and conduct quarterly surveys to fully cover the life history of macroinvertebrates and identify regional scale changes; (2) adopt multiple methods, including the macroinvertebrate multimetric index and macroinvertebrate integrity index, to evaluate the health of water ecosystems and optimize macroinvertebrate health evaluation theory and technology; and (3) combine emerging technologies, such as environmental DNA, high-definition remote sensing, and digital twin, to overcome the arduous technical problems of sampling in plateau rivers.

Acknowledgements. This research was funded by: the National Key R&D Program of China (2022YFC3202605); Special Fund of Chinese Central Government for Basic Scientific Research Operations in Commonweal Research Institutes (Y121012); Central Public-Interest Scientific Institution Basal Research Fund (Y120012, Y122005); and Jiangsu Water Conservancy Science and Technology project (2021069).

LITERATURE CITED

Akyildiz GK, Duran M (2021) Evaluation of the impact of heterogeneous environmental pollutants on benthic macroinvertebrates and water quality by long-term monitoring of the Buyuk Menderes river basin. Environ Monit Assess 193:280

Buss DF, Baptista DF, Nessimian JL, Egler M (2004) Substrate specificity, environmental degradation and disturbance structuring macroinvertebrate assemblages in neotropical streams. Hydrobiologia 518:179–188

Calabria J, Bruton J, Pike J, Brown B and others (2022) Effect of curve numbers on family benthic index in headwater streams in western North Carolina, USA. Environ Chall 7: 100521

Chen K, Hughes RM, Xu S, Zhang J, Cai D, Wang B (2014) Evaluating performance of macroinvertebrate-based adjusted and unadjusted multi-metric indices (MMI) using multi-season and multi-year samples. Ecol Indic 36:142–151

Chen Q, Shi W, Huisman J, Maberly SC and others (2020) Hydropower reservoirs on the upper Mekong River modify nutrient bioavailability downstream. Natl Sci Rev 7: 1449–1457

Chen J, Yang T, Wang Y, Jiang H, He C (2022) Effects of ecological restoration on water quality and benthic macroinvertebrates in rural rivers of cold regions: a case study of the Huaide River, Northeast China. Ecol Indic 142: 109169

Cox B, Oeding S, Taffs K (2019) A comparison of macroinvertebrate-based indices for biological assessment of river health: a case example from the sub-tropical Richmond River Catchment in northeast New South Wales, Australia. Ecol Indic 106:105479

Fierro P, Bertrán C, Mercado M, Peña-Cortés F and others (2015) Landscape composition as a determinant of diversity and functional feeding groups of aquatic macroinvertebrates in southern rivers of the Araucanía, Chile. Lat Am J Aquat Res 43:186–200

Graça MA, Pinto P, Cortes R, Coimbra N and others (2004) Factors affecting macroinvertebrate richness and diversity in Portuguese streams: a two-scale analysis. Int Rev Hydrobiol 89:151–164

Gräfnings MLE, Govers LL, Heusinkveld JHT, Silliman B, Smeele Q, Valdez S, Heide T (2023) Macrozoobenthos as an indicator of habitat suitability for intertidal seagrass. Ecol Indic 147:109948

Grumbine RE, Xu J (2011) Mekong hydropower development. Science 332:178–179

Hilburn BG, Freeman MC, Lawson KM, Rider SJ, Johnsoton CE (2023) Cryptic tolerant fish species and their potential effect on index of biotic integrity (IBI) scores. Ecol Indic 154:110546

Khatri N, Raval K, Jha AK, Rawtani D (2020) Pollution indicators at stretches of the Mahisagar River in Gujarat India. Environ Claims J 32:310–322

Khatri N, Raval K, Jha AK (2021) Integrated water quality monitoring of Mahi river using benthic macroinvertebrates and comparison of its biodiversity among various stretches. Appl Water Sci 11:143

Khatri N, Raval K, Jha AK, Tharmavaram M, Rawtani D (2023) Impact of seasonal changes in the abundance of benthic macroinvertebrates & physico-chemical conditions of a major river in Western India. Environ Claims J 35:157–183

Kitchin PL (2005) Measuring the amount of statistical information in the EPT index. Environmetrics 16:51–59

Kumari P, Maiti SK (2020) Bioassessment in the aquatic ecosystems of highly urbanized agglomeration in India: an application of physicochemical and macroinvertebrate-based indices. Ecol Indic 111:106053

Le CTU, Paul WL, Gawne B, Suter P (2023) Integrating simulation models and statistical models using causal modelling principles to predict aquatic macroinvertebrate responses to climate change. Water Res 231:119661

Li W, Chen Q, Cai D, Li R (2015) Determination of an appropriate ecological hydrograph for a rare fish species using an improved fish habitat suitability model introducing landscape ecology index. Ecol Modell 311:31–38

Liu L, Liu D, Johnson DM, Yi Z, Huang Y (2012) Effects of vertical mixing on phytoplankton blooms in Xiangxi Bay of Three Gorges Reservoir: implications for management. Water Res 46:2121–2130

Liu W, Xu M, Zhao N, Zhou X, Pan B, Tian S, Lei F (2019) River health assessment of the Yellow River source region, Qinghai-Tibetan Plateau, China, based on tolerance values of macroinvertebrates. Environ Sci Pollut Res Int 26:10251–10262

Ludwig JA, Reynolds JF (1988) Statistical ecology: a primer in methods and computing. John Wiley & Sons, New York, NY

Lutz AF, Immerzeel WW, Shrestha AB, Bierkens MFP (2014) Consistent increase in High Asia's runoff due to increasing glacier melt. Nat Clim Chang 4:587–592

Maavara T, Parsons CT, Ridenour C, Cappellen P (2015) Global phosphorus retention by river damming. Proc Natl Acad Sci USA 112:15603–15608

Merovich GT, Frantz MW, Wood PB (2022) Patterns in benthic macroinvertebrate assemblages in an active region of unconventional shale-gas development in the western Appalachian Plateau of West Virginia, USA. Environ Monit Assess 194:368

Ministry of Ecology and Environment of the People's Republic of China (2014) Technical guidelines for biodiversity monitoring—freshwater benthic macroinvertebrates. China Environmental Science Press, HJ 710.8-2014

Ministry of Ecology and Environment of the People's Republic of China (2021) Technical guidelines for monitoring and evaluation of river water ecological environment quality. China Environmental Science Press

Moran EF, Lopez MC, Moore N, Müller N, Hyndman DW (2018) Sustainable hydropower in the 21st century. Proc Natl Acad Sci USA 115:11891–11898

Musonge PS, Boets P, Lock K, Ambarita NMD, Forio MAE, Verschuren D, Goethals P (2019) Baseline assessment of benthic macroinvertebrate community structure and ecological water quality in Rwenzori rivers (Albertine rift valley, Uganda) using biotic-index tools. Limnologica 75: 1–10

Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D (2019) vegan: Community ecology package.

R package version 2.5–6. https://CRAN.R-project.org/package=vegan
Pan B, Wang H, Ban X, Yin X (2015) An exploratory analysis of ecological water requirements of macroinvertebrates in the Wuhan branch of the Yangtze River. Quat Int 380-381:256–261
Poff N, Olden J, Vieiran K, Finn D, Simmons M, Kondratieff B (2006) Functional trait niches of North American lotic insect: traits-based ecological applications in light of phylogenetic relationships. J N Am Benthol Soc 25: 730–755
R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
Ren L, Song S, Zhou Y (2022) Evaluation of river ecological status in the plain river network area in the context of urbanization: A case study of 21 rivers' ecological status in Jiangsu Province, China. Ecol Indic 142:109172
Stranko SA, Hilderbrand RH, Palmer MA (2012) Comparing the fish and benthic macroinvertebrate diversity of restored urban streams to reference streams. Restor Ecol 20:747–755
Su Y, Weiming L, Liu L, Wei H, Jinjing L, Xuyang S, Li Y (2021) Health assessment of small-to-medium sized rivers: Comparison between comprehensive indicator method and biological monitoring method. Ecol Indic 126:107686
Su Y, Fan Z, Gan L, Li Y and others (2023) Assessing lake health in China: Challenges due to multiple coexisting standards. J Hydrol Reg Stud 46:101351
Tachet H, Richoux P, Bournaud M, Usseglio-Polatera P (2002) Invertébrés d'eau douce: systématique, biologie, écologie. CNRS Éditions, Paris
Tang L, Mo K, Zhang J, Wang J and others (2021) Removing tributary low-head dams can compensate for fish habitat losses in dammed rivers. J Hydrol (Amst) 598:126204
van Riemsdijk I, Arntzen JW, Bogaerts S, Franzen M, Litvinchuk SN, Olgun K, Wielstra B (2017) The Near East as a cradle of biodiversity: A phylogeography of banded newts (genus *Ommatotriton*) reveals extensive inter- and intraspecific genetic differentiation. Mol Phylogenet Evol 114:73–81
Vaughan IP, Gotelli NJ (2019) Water quality improvements offset the climatic debt for stream macroinvertebrates over twenty years. Nat Commun 10:1956
Wang X, Xiao X, He Q, Zhang X, Wu J, Li B (2022) Biological invasions in China's coastal zone. Science 378:957
Winemiller KO, McIntyre PB, Castello L, Fluet-Chouinard E, Giarrizzo T, Nam S (2016) Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 351:128–129
Wu P, Zhang H, Wang Y (2015) The response of soil macroinvertebrates to alpine meadow degradation in the Qinghai–Tibetan Plateau, China. Appl Soil Ecol 90:60–67
Wu J, Xu N, Wang Y, Zhang W, Borthwick A, Ni J (2021) Global syndromes induced by changes in solutes of the world's large rivers. Nat Commun 12:5940
Wu X, Chen Z, Cheng C, Yin S, Su H (2022) DNN-SSDP for hydropower system operation using small state sets. J Hydrol (Amst) 614:128612
Wu S, Dong Y, Stoeck T, Wang S, Fan H, Wang Y, Zhuang X (2023) Geographic characteristics and environmental variables determine the diversities and assembly of the algal communities in interconnected river-lake system. Water Res 233:119792
Yan S, Wang X, Zhang Y, Liu D and others (2020) A hybrid PCA-GAM model for investigating the spatiotemporal impacts of water level fluctuations on the diversity of benthic macroinvertebrates in Baiyangdian Lake, North China. Ecol Indic 116:106459
Yi Y, Sun J, Yang Y, Zhou Y, Tang C, Wang X, Yang Z (2018) Habitat suitability evaluation of a benthic macroinvertebrate community in a shallow lake. Ecol Indic 90: 451–459
Zhang Z, Li Y, Wang X, Li H and others (2021) Assessment of river health based on a novel multidimensional similarity cloud model in the Lhasa River, Qinghai-Tibet Plateau. J Hydrol (Amst) 603:127100
Zhang Z, Li Y, Wang X, Li H and others (2022) Lake ecosystem health assessment using a novel hybrid decision-making framework in the Nam Co, Qinghai-Tibet Plateau. Sci Total Environ 808:152087
Zhou X, Xu M, Wang Z, Yu B, Shao X (2019) Responses of macroinvertebrate assemblages to environmental variations in the river-oxbow lake system of the Zoige wetland (Bai River, Qinghai-Tibet Plateau). Sci Total Environ 659: 150–160
Zhou XD, Xu MZ, Lei FK, Zhang JH, Wang ZY, Luo YY (2022) Responses of Macroinvertebrate assemblages to flow in the Qinghai-Tibet Plateau: establishment and application of a multi-metric habitat suitability model. Water Resour Res 58:e2021WR030909

Editorial responsibility: J. Rudi Strickler, Milwaukee, Wisconsin, USA
Reviewed by: R. de Souza Rezende, N. Khatri and 1 anonymous referee

Submitted: June 20, 2023
Accepted: November 3, 2023
Proofs received from author(s): January 19, 2024