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Urban stream rehabilitation in a densely populated Brazilian metropolis

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Environmental rehabilitation of urban streams has been widely applied in Global North countries, at least since the 1970s, but it is a recent approach in Global South countries. The objective of this paper is to evaluate whether the rehabilitation experience carried out since 2006 in three urban stream sites in the third-largest Brazilian metropolis (c. 5.5 million inhabitants) was and continues to be effective in terms of socio-environmental improvement after 10 years of interventions. These interventions included the rehabilitation of watercourses (e.g., improvement of water quality through the management of sewage and garbage, stabilization of riverbanks, revegetation of riparian zones, riverbed naturalization, removal of riverbank housing). We evaluated water quality, physical habitat structure, and benthic macroinvertebrate assemblages in three test sites in three sampling periods: pre-intervention (2004–2005), early post-intervention (2008–2011) and late post-intervention (2018–2019). Additionally, three reference-stream sites (2018–2019) were assessed to compare the conditions of the three tested sites versus the reference sites. We also assessed citizen perceptions concerning the interventions through questionnaires given to urban stream residents at the three tested sites in early and late post-rehabilitation (215 in 2008, 180 in 2019). The results of water quality monitoring showed a significant improvement in most parameters used to calculate the Water Quality Index (WQI) in the early intervention phase, and WQI scores have improved since. The physical habitat and macroinvertebrate indicators indicated moderate improvements. The residents indicated increased appreciation of the environmental improvements over 10 years. Given the results in Belo Horizonte, we believe that implementation and evaluation of similar projects and programs aimed at rehabilitating urban streams are technically viable using our approaches throughout the Global South.

KEYWORDS

Belo Horizonte, Brazil, Drenurbs Program, multitemporal monitoring and assessment, before/after control/impact assessment - BACI, water quality, benthic macroinvertebrate, citizen perception

1 Introduction

Humanity arrives in the 21st century with the highest percentage of its population distributed in urban areas (Bernhardt and Palmer, 2007; Ranta et al., 2021), and this population has been severely degrading watercourses, with planners not considering the importance of rivers in urban design (Wantzen et al., 2019). This occurs because urbanization degrades water body quality through eutrophication, alters physical habitat structure and flow regimes, and increases relative abundances of species tolerant to anthropogenic pressures (Bernhardt and Palmer, 2007; Paul and Meyer, 2008; Feio et al., 2021). Such changes severely compromise the biotic integrity and ecosystem services of urban lotic ecosystems (França et al., 2019; Feio et al., 2021).

To improve urban stream conditions, stream restoration and rehabilitation interventions can be used to recover the ecosystems. Restoration is the process of intentionally returning a site to its natural form through processes and interventions that lead to reconstructing its structure, function, diversity and dynamics, according to its historical (natural) characteristics (Findlay and Taylor, 2006; Bernhardt andPalmer., 2007). However, it is extremely difficult for river and stream restoration to remove or minimize all human pressures in urbanized catchments. In addition, reference sites for determining natural ecosystem conditions are exceedingly rare (Wade et al., 1998; Brierley and Fryirs, 2000). Even when these conditions are known, the current hydrological and land use dynamics do not allow actions to return ecological conditions to the pristine stage (Wade et al., 1998). Thus, rehabilitation interventions, in which the objectives are an improvement of the fluvial state based on the recovery of some elements, processes or ecological functions offer more appropriate goals. Such interventions can bring watercourses closer to their pre-disturbance conditions, but without achieving full recovery (restoration) of the ecosystems (Brierley and Fryirs, 2000). Common stream rehabilitation projects result in channel realignments, riparian plantings, increased channel physical complexity, and urban parks (Hughes et al., 2014b; Hughes, 2019). Therefore, rehabilitation is a more probable goal, especially in heavily urbanized areas.

Stream rehabilitation projects have been developed by public agencies in several countries of the Global North such as United States, United Kingdom, Canada, European Union, Japan, South Korea, Australia, and New Zealand for at least 50 years (Macedo and Magalhães Jr., 2020; Feio et al., 2021). These projects are driven by laws established to conserve and recover river environments (Palmer et al., 2005; Hughes et al., 2014b; dos Reis Oliveira et al., 2020). Such laws have been followed by exponential increases in the number of rehabilitation projects, scientific research, and scientific journal publications (Bernhardt et al., 2005), of which most are in the United States and Europe (~ 40% in each) (dos Reis Oliveira et al., 2020). In the Global South, South American countries have few documented examples of rehabilitation interventions (but see Wantzen et al., 2019), focused mainly on sewage collection systems, rehabilitation of riverbanks through engineering and bioengineering techniques, rehabilitation of riparian vegetation, and flood mitigation (Feio et al., 2021).

The lack of rehabilitation projects in Global South countries is partly explained by the lack of financial resources and by the lack of a legal framework aimed at conserving and rehabilitating watercourses (Feio et al., 2021). A third factor, mainly in Brazil, is the lack of social pressure demanding urban stream rehabilitation projects because local populations are unaware of the possibilities and effectiveness of such interventions (Macedo and Magalhães Jr, 2011; Hong and Chang, 2020). However in Brazil, there are several proposals for river rehabilitation found in the gray literature, but few examples of implementation and results monitoring. Thus, the city of Belo Horizonte provides the best documented case study that was surveyed both before and after rehabilitation phases (Macedo et al., 2011; Macedo and Magalhães Jr, 2011; Feio et al., 2015, 2021; Macedo and Magalhães Jr., 2020).

Despite significant increases in the number of rehabilitation projects in urbanized areas in recent years, < 10% have been monitored to document improvements in environmental quality, especially via pre- and post-intervention comparisons (Bernhardt et al., 2005; Al-Zankana et al., 2020). Of those, the most-used assessment tools are instream physical habitat structure and riparian conditions, benthic macroinvertebrate assemblages, and physical and chemical water quality (Palmer et al., 2014; Kail et al., 2015; Al-Zankana et al., 2020). But few studies have assessed all those factors together (e.g., Davis et al., 2003; Selvakumar et al., 2010). Assessments of citizen perceptions of rehabilitation interventions are infrequent (Hong and Chang, 2020); although it is important to assess the support that the surrounding human citizens have on the interventions, especially concerning conservation over time (Bernhardt and Palmer, 2007). Relatively few studies have assessed citizen perceptions in rehabilitation projects (Purcell et al., 2002; Larned et al., 2006). Thus, more studies using these four assessment tools (i.e., instream physical habitat structure and riparian conditions, benthic macroinvertebrate assemblages, physical and chemical water quality, and citizen perception), through before/after control/impact (BA/CI) assessment approaches are needed.

In this context, our objective was to evaluate the long-term (2008–2019) results of the 2006–2007 stream rehabilitation interventions carried out in Belo Horizonte considering water quality, instream physical habitat structure and riparian conditions, macroinvertebrate assemblage condition, and citizen perceptions. Our first premise was that rehabilitation produces a progressive improvement in all ecological components. However, as a result of the severe effects of

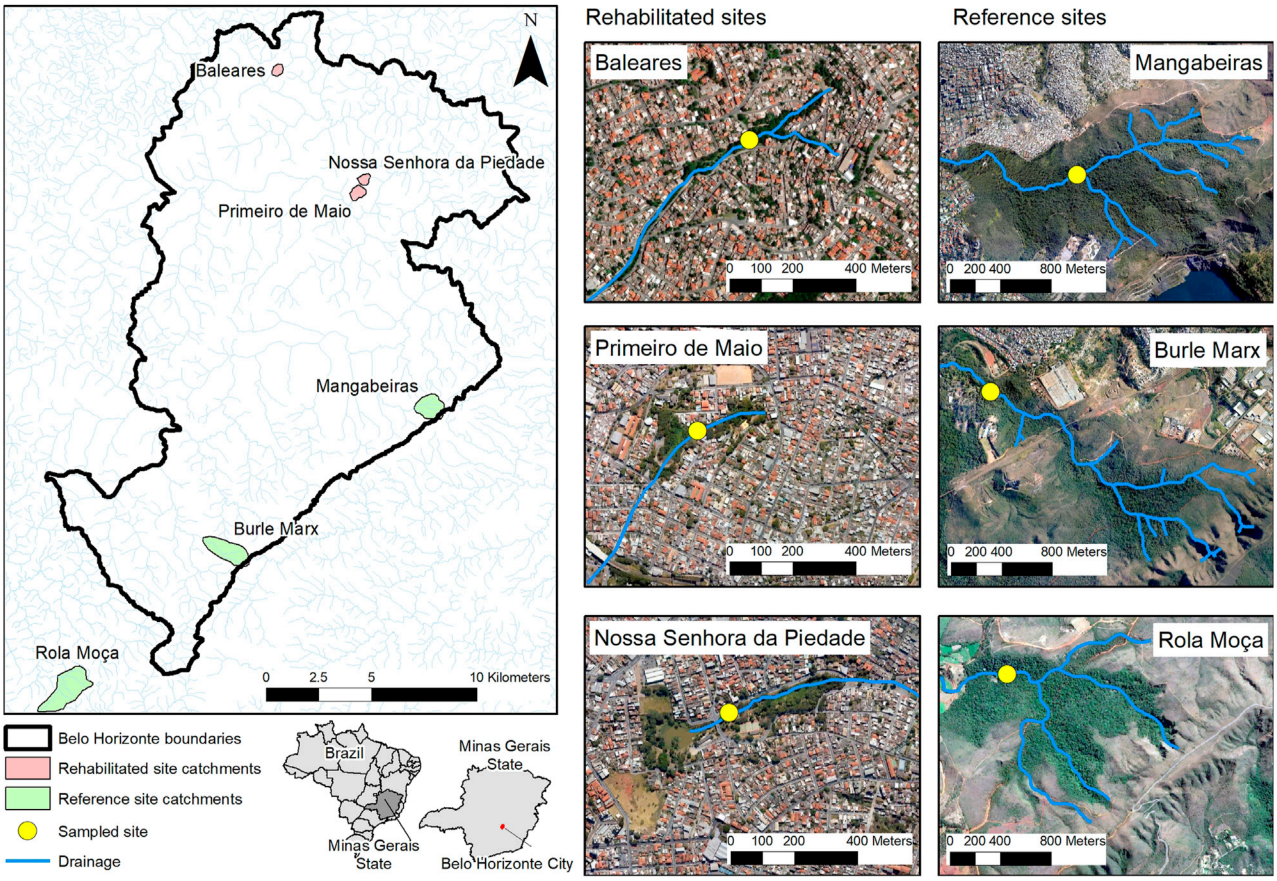

FIGURE 1
Map of study area, showing the test- and reference-stream sites.

urbanization, we did not expect that the rehabilitated stream sites would attain the ecological conditions occurring in minimally disturbed reference sites. Our second premise was that the areas surrounding the rehabilitated sites, as well as the sites themselves, would improve ecosystem services measurably for the local human populations.

2 Methods

2.1 Study area

Three stream sites were assessed in Belo Horizonte, the third-largest Brazilian metropolis (c. 5.5 million inhabitants) (Baleares, Primeiro de Maio, and Nossa Senhora da Piedade; Figure 1). The rehabilitation was conducted by the Drenurbs Program of the Belo Horizonte Municipal Government using Inter-American Development Bank financial support (60% of the US$ 14.53 million was spent in these 3 streams; BID, 2008). Before the rehabilitation interventions, the streams had deficient drainage infrastructure, human occupation of the streambank and floodplains; inputs of untreated sanitary sewage in the natural stream channels; disposal of garbage in streams, and deforestation and erosion on the streambank and hillside. The site interventions occurred between 2006 and 2007 and included: (1) sewage collection networks and sewage treatment; (2) improvement of stormwater drainage systems; (3) bank erosion control and stabilization via artificial structures like gabions and walls; (4) streambank stabilization using geotextiles and revegetation of riparian zones using woody tree species; (6) stream bed stabilization using fixed boulder clusters; (7) flood control systems using detention basins; (8) removal of houses from floodplains and riverbanks; and (9) creation of a protected area with riparian parkland (Figure 2). The pre-rehabilitation condition of each site differed concerning the degree of impact and the population affected, which required different solutions in terms of costs and populations relocated. For instance, a slum was present along Baleares stream, but Primero de Maio was bordered predominantly by degraded grassland and few houses. Because of local morphology, the

FIGURE 2
Partial views of sites before rehabilitation (left) in 2003 (photos by UEP/DRENURBS/Prefeitura de Belo Horizonte) and after rehabilitation (right) in 2019 (photos by D.R. Macedo). **(A)** Baleares; **(B)** Primeiro de Maio; **(C)** Nossa Senhora da Piedade.

Baleares parkland is steeper than the others and occupies less area (25–45 m wide, 21,900 m^2 total area). Primeiro de Maio and Nossa Senhora da Piedade parklands have similar morphology and occupy larger areas (50–100 m and 55–170 m wide and 33,500 m^2 and 57,200 m^2 in area for Primeiro de Maio and Nossa Senhora da Piedade respectively). Both also had structures installed to mitigate freshets (Table 1). All the parks encourage visitors because recreational (workout) equipment and walking paths were installed. Additionally, Primeiro de Maio and Nossa Senhora da Piedade have sport courts. Woody species were placed near the streams (~10–15 m), but grass areas are maintained for public uses.

Additionally, three reference sites, located in urban protected areas and water-collection areas within the Belo Horizonte metropolitan area were selected as control sites (Mangabeiras Municipal Park, Rola Moça State Park, and Burle Marx Municipal Park). These three reference sites were also on headwater streams (3rd order streams with < 2 km^2 total catchment area and 1–2 km long) with > 90% natural cover. They were chosen because they are the closest preserved areas to the rehabilitated streams and are in the best available ecological condition (Figure 3).

2.2 Assessment sampling design

To assess changes in water quality, instream habitat, riparian conditions, macroinvertebrate multimetric indices (MMIs), and taxonomic composition of benthic macroinvertebrate assemblages in the rehabilitated stream sites, we used data

TABLE 1 Budgets for the rehabilitation of Baleares, Primeiro de Maio, and Nossa Senhora da Piedade streams between 2006 and 2008 (from BID, 2008; Macedo and Magalhães Jr. 2020).

Stream site	Total catchment area (km^2)	Total stream length (km)	Total catchment population (inhabitants)	Total riparian park area (m^2)	Investments (millions of dollars)		
					Inter-vention	Indemnities and expropriations	Total
(1) Baleares	0.73	1.1	6,713	21,901	2.18	0.91	3.10
(2) Primeiro de Maio	0.48	0.8	2,983	33,522	1.83	0.48	2.30
(3) Nossa Senhora da Piedade	0.43	0.6	3,741	57,239	5.88	3.26	9.13

FIGURE 3
Reference sites in best available ecological condition: **(A)** Mangabeiras Municipal Park; **(B)** Serra do Rola Moça State Park; **(C)** Burle Marx Municipal Park.

collected between 2003 and 2011 so that each site was visited at least 4 times a year (twice in the dry season, and twice in the rainy season) (PBH 2012; Feio et al., 2015; Macedo and Magalhães Jr., 2020). Additionally, four sampling visits were carried out (two in the dry season, and two in the rainy season) in 2018–2019, in both rehabilitated and reference stream sites. This allowed separating our dataset into four groups: pre-rehabilitation (2003–2005), early post-rehabilitation (2008–2011), later post-rehabilitation (2018–2019), and reference sites (2018–2019). To assess citizen perceptions of the stream interventions, we used questionnaires applied to randomly selected households within 150 m of the 3 rehabilitated stream sites in 2008 (n = 215) (Medeiros, 2009; Macedo and Magalhães Jr, 2011), and in 2019 (n = 180).

2.3 Water quality assessment

Water quality was evaluated *in-situ* for temperature (°C), pH, turbidity (NTU) and total dissolved solids (mg/L), using a multiparameter probe (YSI - 10 - Yellow Springs, Ohio). In addition, 2 L of water was collected during each stream site-visit, iced, and analyzed in the laboratory for dissolved oxygen (mg/L), biochemical oxygen demand (mg/L), total phosphorus (mg/L), nitrate (mg/L), and *Escherichia coli* (MPN/100 ml) (APHA 2005). These parameters were compared against national and state water quality criteria (Brazil, 2005; Minas Gerais, 2008; Table 2). Additionally, these 9 parameters were integrated into the Water Quality Index (WQI) used in the state of Minas Gerais, which classifies water status as very bad (< 25), bad (25–50), fair (50–70), good (70–90) and very good (90–100). To calculate the WQI, we used the weighted product of each evaluated parameter (Table 2) and the value of the parameter obtained through the specific average quality curve where each parameter result has a scale between 0 and 100 (e.g., 20% dissolved oxygen saturation is 12; pH of 6 is 52; turbidity of 10 is 76) (Supplementary Material S1).

2.4 In-stream habitat and riparian condition assessment

To assess the physical habitat and riparian zone conditions, we applied a rapid assessment protocol (Callisto et al., 2002). This

TABLE 2 National Brazilian and Minas Gerais state legal limits for class 2 water quality variables and their weights in a Water Quality Index (WQI).

Water quality parameters	Class 2 legal limit (Federal and State)	Weight in WQI
Dissolved Oxygen	> 5 mg/L	0.17
Escherichia coli	< 1,000 MNP/100 ml	0.15
pH	Between 6.0 and 9.0	0.12
Total Phosphorus	< 0.10 mg/L	0.10
Nitrate	< 10 mg/L	0.10
Biochemical Oxygen Demand	< 5 mg/L	0.10
Water temperature	No legal criteria; °C variability to WQI	0.10
Turbidity	< 100 NTU	0.08
Total Dissolved Solids	< 100 mg/L	0.08

protocol allows a rapid assessment through visual observations of the ecomorphological conditions in the stream channel and the riparian zone of sites (Supplementary Material S2). The assessment was based on a set of environmental parameters scored from zero to four (referring to the use and occupation of the riparian zone and the apparent characteristics of the water); and from zero to five (flow and substrate conditions important for aquatic biota). The protocol is synthesized in a final score that reflects the level of conservation of the ecomorphological conditions of each stream site, where 0–40 represents impaired sites, 41–60 altered sites, and > 61 reference condition sites (Callisto et al., 2002; Feio et al., 2015; França et al., 2019).

2.5 Benthic macroinvertebrate assemblage assessment

We collected three bottom subsamples with a kick-net sampler (30-cm opening, 0.09 m^2 area, 500-µm mesh) in each stream site, preferably one subsample in pebbles/gravel, another in fine sediments (sands and silts), and a third in leaf deposits. The sub-samples were individually placed in plastic bags and fixed with 70% alcohol. In the laboratory, we washed the subsamples with tap water, sorted the benthic macroinvertebrates, and identified individuals to family, except to suborder for Hydracarina, class for Bivalvia, and subclass for Oligochaeta. The organisms were identified under a stereomicroscope, by using taxonomic keys (Fernández and Domínguez, 2001; Costa et al., 2006; Merritt et al., 2008; Mugnai et al., 2010; Hamada et al., 2014), and the three subsamples were combined into a single composite sample for each site visit. Benthic macroinvertebrates were deposited in the Reference Collection of Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais.

The biological data of each stream were used to calculate four biological metrics that constitute a multimeric index (MMI; Macedo et al., 2016): Ephemeroptera-Plecoptera-Trichoptera (EPT) taxa richness; Average Tolerance Score per Taxon (ASPT), Percentage of Predator individuals, and Percentage of Odonata individuals. These metrics were standardized to the same scale (0–100) considering all sites together and then the metrics were divided by their 95th percentile and multiplied by 100. Values above 100 were considered super optimal and were scored as 100. The final MMI was calculated as the average of its standardized biologic metrics.

2.6 Citizen perception assessment

To evaluate citizen perceptions of the rehabilitated stream sites, questionnaires composed of multi-option objective questions were applied *in loco* at 180 randomly selected households (60 questionnaires, one for each home within 120 m of each of the three stream sites) in July 2019. The questions were guided to measure the use of linear parks, population satisfaction with the rehabilitation interventions, and questions related to the social dynamics concentrated in the study areas. The questionnaire was structured with qualitative and quantitative questions, and finalized after a pre-test survey (i.e., application of a questionnaire in its preliminary version in only few households to adjust it). The respondents did not have access to the options, instead the interviewers marked the answers within the pre-existing options, or in the option "other" where the answer was described. After tabulation, responses were classified (e.g., "great" and "good" were grouped in "great or good"). When necessary, multi-option answers were entered (i.e., an interviewer could mark one or more options). Answers also were post-processed because some of the "other" answers could be categorized during data tabulation. We compared those results with an earlier 2008 survey based on 215 questionnaires also applied randomly near the three rehabilitated sites (Medeiros, 2009; Macedo and Magalhães Jr, 2011). In both dates, we used

Belo Horizonte's official address database to randomly select our homes. We used systematic repositioning procedures to change a sampled household when a household presented a refusal. We considered all the households within 120 m as our study population, so we can infer results to 1,490 and 1,550 homes in 2008 and 2019, respectively (PBH, 2012). To maintain temporal comparability, an adaptation of the questionnaire applied in 2008 (Supplementary Material S3) was used in 2019 (Supplementary Material S4). The questions were organized to assess general interviewee profile (i.e., sex, age, and education), perceptions concerning the positive and negative points (multiple answers allowed), solution of environmental problems, general satisfaction with the interventions, and preference for riparian park versus stream burial by an elevated road. The latter has been a common practice in Belo Horizonte, where approximately 200 km of streams have been covered by roads (~30% of the city's streams; PBH, 2022). Riparian stream parks were a new idea before 2008 in Brazil.

2.7 Data analyses

2.7.1 Water quality assessment, in-stream habitat and riparian condition, and biotic condition

The measures of the 9 water quality parameters, WQI, in-stream habitat and riparian condition, and benthic macroinvertebrate MMI were grouped in four period-groups (pre-rehabilitation (2003–2005), early post-rehabilitation (2008–2011), late post-rehabilitation (2018–2019), and reference stream sites (2018–2019). The data were combined for each of the four time-periods and averaged for each stream site because of their high seasonal correlations. Those averages were analyzed by analysis of variance with two factors (two-way ANOVA), but with one of the factors being blocked (Montgomery and Runger, 2018), followed by Tukey's HSD (honestly significant differences) post-hoc tests to determine whether differences between groups were significant. The analysis used the times and sites as blocks versus predictor variables. Thus, there were four time-blocks: pre-rehabilitated sites, early post-rehabilitated sites, late post-rehabilitated sites, and reference sites. Similarly, there were four site-blocks: Baleares, Primeiro de Maio, Nossa Senhora da Piedade, and reference sites. Before proceeding with the analyses, the variables were inspected using qq-plots, and those that did not show a normal distribution were transformed using the Box-Cox method (Box and Cox, 1964). All models assumed homogeneity of variance; normality and independence of residuals were validated.

2.7.2 Benthic macroinvertebrate composition

Benthic macroinvertebrate assemblage composition was grouped in four groups: pre-rehabilitation (2003–2005), early post-rehabilitation (2008–2011), late post-rehabilitation (2018–2019), and reference sites (2018–2019). To test if there was significant difference between taxonomic composition between the four groups we used multivariate permutation analysis of variance (PERMANOVA) and non-metric multidimensional scaling (nMDS) based on the Bray-Curts index to determine changes in assemblage composition.

2.7.3 Citizen perceptions

Data were analyzed by combining the responses for the three rehabilitated sites. We considered each variable as a binomial random response (i.e., yes or no), so we created 95% confidence intervals for proportions (Montgomery and Runger, 2018) to compare 2008 and 2019 questionnaire sets of answers. Our error margin was about 6%, considering the total population as 1,490 and 1,550 households in 2008 and 2019, respectively. To evaluate whether opinions changed regarding positive and negative aspects, as well as two fundamentally different types of interventions: channel-riparian rehabilitation (riparian stream park), versus stream burial, we used Pearson's chi-squared test using 2008 and 2019 as groups. To evaluate the differences in opinions to general evaluation and if the environmental problems were solved, we used chi-squared goodness of fit in the 2019 survey results. All statistical analyses were performed in R, using the "survey", "FSA," "labdsv," and "vegan" packages.

3 Results

3.1 Water quality

Overall, the three rehabilitated stream sites showed progressive improvement in water quality over time. Most parameters within national Brazilian and Minas Gerais state legal limits for class 2 rivers (Brazil, 2005; Minas Gerais, 2008) were achieved in post-rehabilitation early and late phases, except for total dissolved solids, pH, water temperature, WQI, and *Echerichia coli* (Figure 4). Total phosphorus, dissolved oxygen, biochemical oxygen demand, turbidity, and WQI showed improvements, with most of the values in the later post-rehabilitation phase meeting class 2 water quality criteria (meaning that the waters were safe for human recreational primary contact). Nitrate concentrations were reduced, but were within the legal limits before the interventions. Temperature and pH remained somewhat higher than in the reference stream sites. All three reference stream sites met the federal and state water quality limits. The later post-rehabilitation stream sites had levels of total phosphorus, dissolved oxygen, biochemical oxygen demand, turbidity, and pH that were not statistically different from those in the reference stream sites. However, WQI scores differed significantly between later post-intervention stream sites versus reference stream sites, mainly because of higher levels of *Escherichia coli* and total dissolved solids.

3.2 Physical habitat and riparian condition

Instream physical habitat and riparian zone conditions indicated improvement following rehabilitation (Figure 5A).

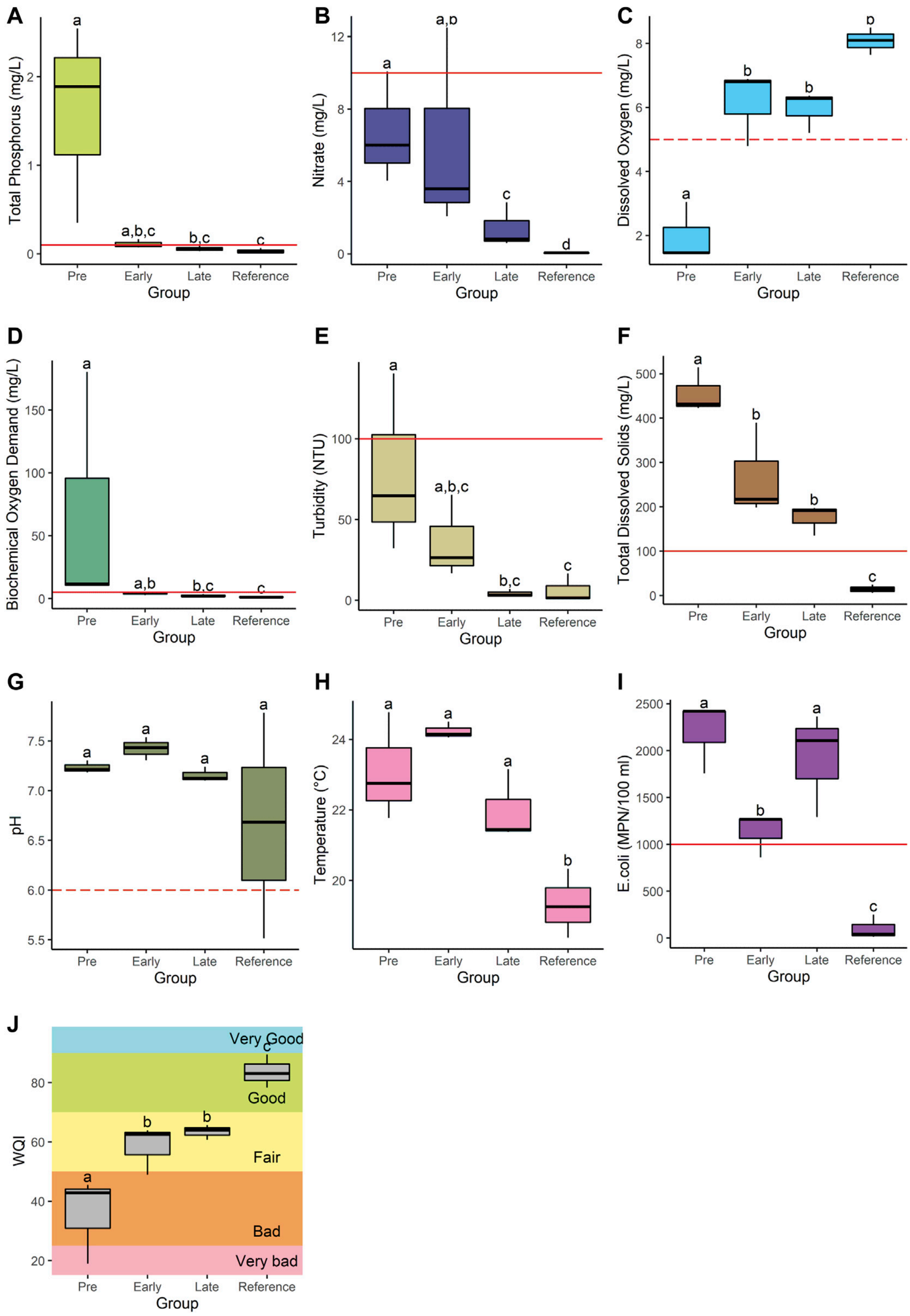

FIGURE 4
Differences in water quality at pre-rehabilitation, early post-rehabilitation, later post-rehabilitation, and reference sites: **(A)** Total phosphorus; **(B)** Nitrate; **(C)** Dissolved Oxygen; **(D)** Biochemical Oxygen Demand; **(E)** Turbidity; **(F)** Total Dissolved Solids; **(G)** pH; **(H)** Water temperature; **(I)** *Escherichia coli* and **(J)** Water Quality Index. The continuous red lines represent legal upper limits and dashed red lines, the lower legal limits for water class 2.

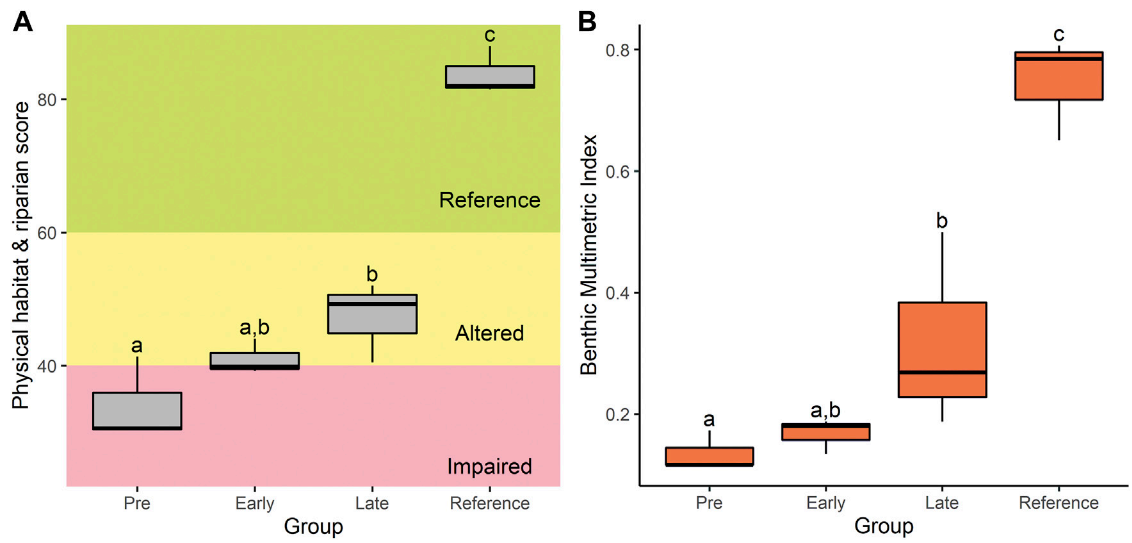

FIGURE 5
Differences in physical habitat structure and multimetric index scores pre-rehabilitation, early post-rehabilitation, late post-rehabilitation, and reference sites: **(A)** Instream physical habitat and riparian zone index scores; **(B)** Benthic multimetric index scores.

Prior to rehabilitation, scores were concentrated in the impaired zone (< 40 points) and in the early and late post-rehabilitation periods, they were within the altered range (40–60), but showing progressive improvements. However, the scores were significantly lower than those of the reference stream sites (generally close to 80 points).

3.3 Macroinvertebrate assemblage condition

Similar to the water quality and physical habitat results, the MMI results indicated progressive improvement over time (Figure 5B) and MMI and physical habitat scores were highly correlated with each other (Pearson's $r = 0.96$). Before rehabilitation, MMI scores were very low (< 0.2), but improved significantly in both post-rehabilitation phases. However, assemblage condition remained significantly below that in the reference sites.

The taxonomic composition of the benthic macroinvertebrate assemblages in the three rehabilitated sites differed from the reference sites in all sampling periods. The Bray-Curtis index scores indicated that all possible pairings differed significantly (Table 3) and the nMDS results show a noticeable shift in late post-rehabilitation towards the reference sites (Figure 6).

TABLE 3 Permutational multivariate analysis of variance pairwise tests comparing the taxonomic composition of benthic macroinvertebrate assemblages of rehabilitated and reference sites over time periods.

Pairs	F Model	R^2	P adjusted
Pre vs. Early post	5.791405	0.0841879	0.0006
Pre vs. Late post	6.129386	0.109201	0.0006
Pre vs. Reference	11.471684	0.1866174	0.0006
Early post vs. Late post	5.440622	0.1345336	0.0006
Early post vs. Reference	9.168435	0.2075789	0.0006
Late post vs. Reference	4.538342	0.1710108	0.0006

3.4 Citizen perceptions

All urban riparian parks surroundings had similar profile about sex, age and education pattern (Table 4). More positive aspects than negative ones were reflected in the 2008 and 2019 questionnaire results (Figures 7A,B). As expected, some of the positive aspects were more evident soon after the interventions, such as cleaning the river (60 % vs. 5% in 2008 and 2019, respectively, $X^2 = 131.282$; df = 1, $p < 0.0001$) or completing the park (51% in 2019 and 18% in 2008, $X^2 = 50.931$; df = 1, $p < 0.0001$). Other aspects were mentioned only at one time period, such as improving road access by 25% in 2008 and removing the slum, which was answered by 9% in 2008, or creating a space for community use, which was remembered only in 2019 for 18%. Other positive aspects have similar values over time, with emphasis on the creation of leisure areas (45%; $X^2 = 0.46$; df = 1, $p = 0.831$), improvement of aesthetic aspects (15 % and 20%; $X^2 = 1.64$; df = 1, $p = 0.2$), decreased flood risk (2 % and 3%; $X^2 = 1.64$; df = 1, $p = 0.2$, and improved real estate value (4% and 1.6%; $X^2 = 2.134$; df = 1, $p = 0.144$).

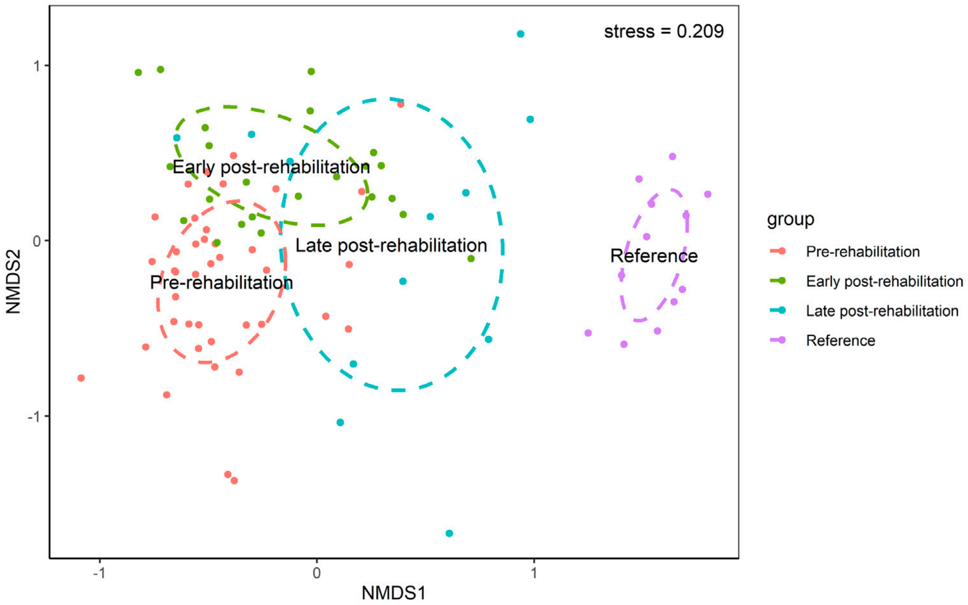

FIGURE 6
Non-metric Multi-dimensional Scaling comparing the taxonomic composition of benthic macroinvertebrate assemblages of rehabilitated and reference sites among the four time-groups.

TABLE 4 Sociodemographic profile of population surveyed into 3 rehabilitated riparian parks surroundings.

		Urban Riparian Park		
		Primeiro de Maio	**Nossa Senhora da Piedade**	**Baleares**
Sex	Female	70	83	85
	Male	51	53	53
Age	17 to 20	10	16	4
	21 to 30	17	16	17
	31 to 40	27	23	25
	41 to 50	28	23	26
	51 to 60	11	22	25
	More than 60	28	36	41
Education	Illiterate	2	2	7
	Read and Write	15	29	23
	Elementary School	51	50	51
	Middle School	45	41	43
	High School	7	12	10
	College	1	2	4

Negative aspects were pointed out by fewer residents (< 15%), however with lower values 10 years after the rehabilitation, indicating good results from the interventions. Local citizen perceptions improved regarding increased security 13 %–3% in 2008 and 2019, respectively (X^2 = 16.35; df = 1, p < 0.0001). Some aspects showed no differences between the 2 years: 3 % and 1.6% considered that road system worsened (2008 and 2019, respectively; X^2 = 0.566; df = 1, p = 0.452) and people

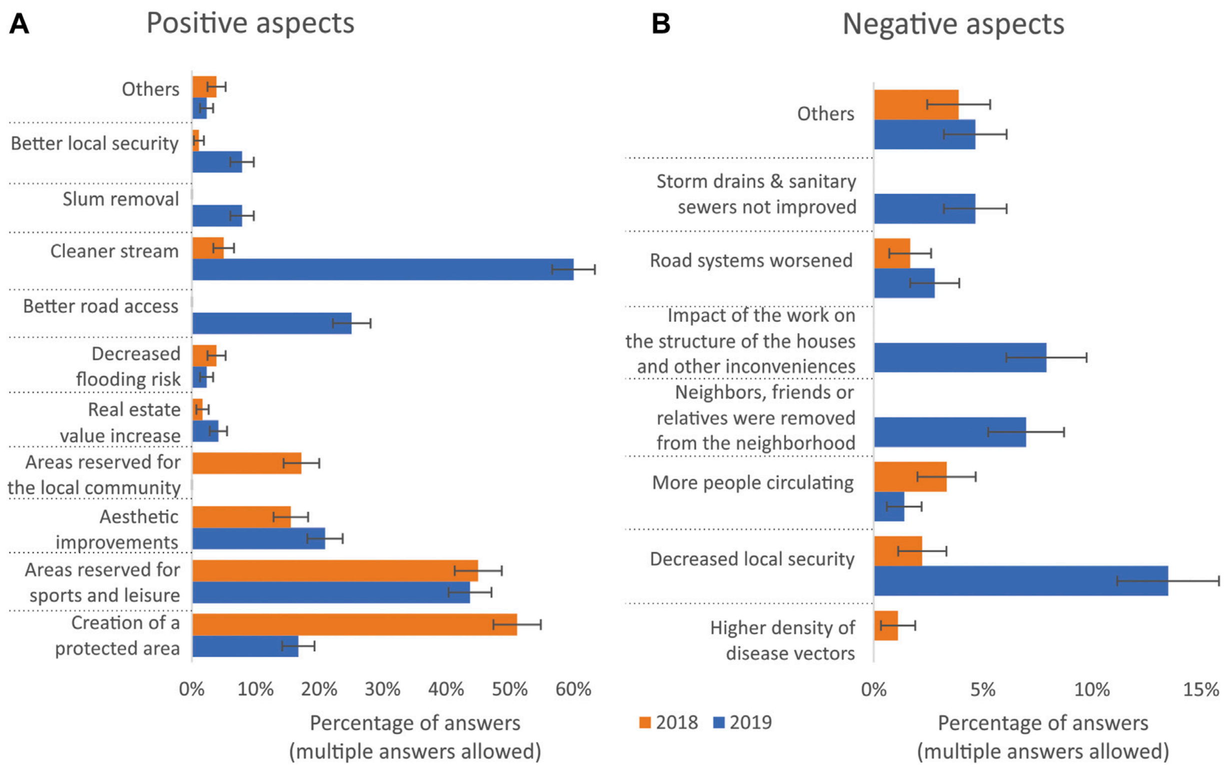

FIGURE 7
(A) Positive and **(B)** negative aspects regarding rehabilitation measures in 2008 and 2019. Bars are means; whiskers are 95% confidence intervals.

circulation were a negative aspect to 1.3 % and 3%; (X^2 = 1.634; df = 1, p = 0.201). Other aspects were only mentioned after the interventions, such as the impact of construction disturbances (8%), the removal of neighbors and relatives (7%), and that drainage and sewage system problems had not been solved (5%).

In general, the acceptance of the interventions was and remains very high in 2019, with more than 83% approval by citizens, while 5% disapproved (X^2 = 166.23; df = 2, $p < 0.0001$). In addition, 65% of respondents said that the environmental problems were solved, 30% partially, which reinforces social acceptance (X^2 = 75.57; df = 2, $p < 0.0001$) (Figure 8). Finally, the survey results show that the linear stream park was preferred by 58% in 2008, but it was preferred by 90% versus stream burial in 2019, showing there has been a significant increase in people who prefer the rehabilitated stream after 10 years of rehabilitation interventions (X^2 = 51.07; df = 1, $p < 0.0001$; Figure 9).

4 Discussion

We aimed to assess whether the stream rehabilitation interventions carried out in Belo Horizonte in 2006–2007 produced useful results 10 years later. Significant improvements were found in water quality, in-stream habitat, riparian zones, and macroinvertebrate assemblages comparing pre- and post-interventions. However, the results remained below reference site conditions, indicating that "restoration" to natural conditions is unlikely, corroborating the idea that return to the natural state in an urbanized area is an unrealistic goal (Hughes et al., 2014b; da Silva and Porto, 2021). In this regard, it is important to align ecological expectations with reality (Loflen et al., 2016). The impacts of urban areas on streams result from multiple, complex, point- and diffuse-sources combined with natural annual and seasonal variability. Our sampling design, repeated at least four times annually over 16 years, aimed to better diagnose this temporal variation; however, we observed insignificant intra- or inter-seasonal differences. This suggests that sampling once during the dry season should suffice for making ecological assessments such as ours, thereby reducing monitoring and assessment costs (Hughes and Peck, 2008; Fierro et al., 2021; Callisto et al., 2022; Kaufmann et al., 2022).

4.1 Water quality

The implementation of sewage networks, garbage collection, streambank stabilization, and riparian vegetation recovery improved water quality to the degree that most indicators met most Brazilian national and state standards for Class 2 waters

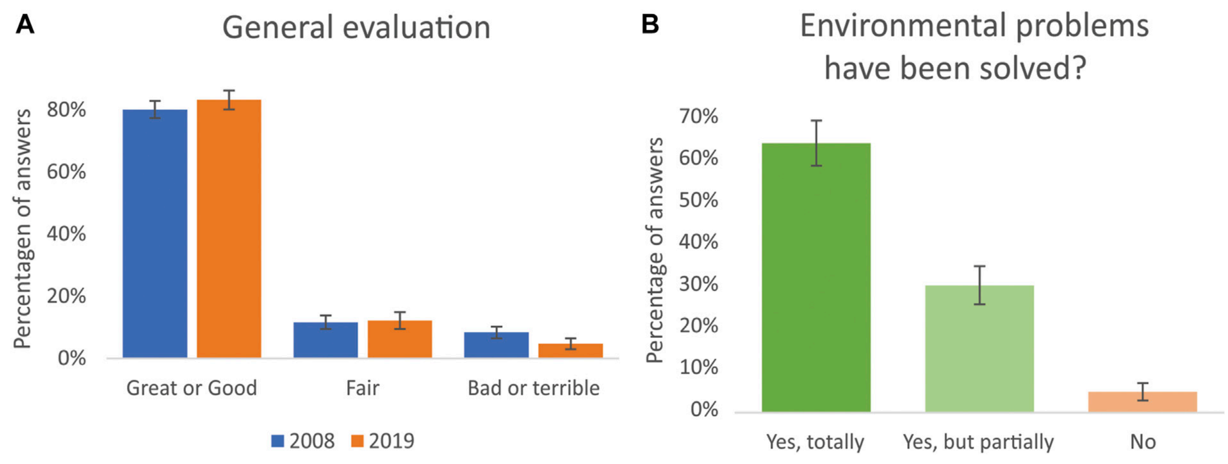

FIGURE 8
Acceptance of rehabilitation projects: **(A)** general evaluation and **(B)** if major environmental problems were solved.

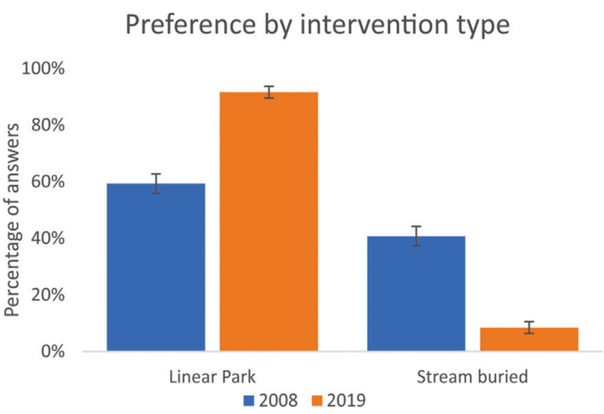

FIGURE 9
Preference by intervention type in 2008 and 2019.

(Brazil, 2005; Minas Gerais, 2008). Those standards are deemed sufficient to protect aquatic communities, primary water-recreational activities, irrigation, aquaculture, and drinking water supply after conventional treatment. Reduced organic loads resulting from the rehabilitation interventions are verified by improved water quality indicator scores (Wantzen et al., 2019), including total phosphorus, nitrate, dissolved oxygen, turbidity, biochemical oxygen demand, and WQI. Four of those parameter values (pH, total phosphorus, turbidity, biochemical oxygen demand) did not differ significantly from those at reference sites (two of which are springs used for drinking water), indicating recovery of water quality for those parameters. However, total dissolved solids and water temperature, despite improvement, still exceed the desired limits. Water temperature and total dissolved solids concentrations are linked to surface runoff from the entire catchment, which is difficult to control without stormwater collection and treatment (Paul and Meyer, 2008; Loflen et al., 2016). Because of sewage collection, *Escherichia coli* and total dissolved solids now are related to surface runoff, which was not controlled in the rehabilitated sites, and which therefore lowered WQI scores. Achieving legal standards is a useful goal for rehabilitation projects (Hughes et al., 2014b); therefore, because Brazil lacks standards for physical habitat and aquatic assemblages (Feio et al., 2021), achieving water quality goals is a relevant outcome.

The *Escherichia coli* values were lower in early post-rehabilitation than in late post-rehabilitation, although they exceeded water quality standards in both cases as well as in pre-rehabilitation. Because *Escherichia coli* occur in the lower gastrointestinal tract of warm-blooded organisms, it would be useful to investigate whether the contamination in the latter post-rehabilitation phase is associated with increased incidence of animals attracted to the parks (Soller et al., 2010).

4.2 Stream and riparian physical habitat

Several studies point to the importance of stream and riparian habitat structure in the ecological rehabilitation of streams (Bernhardt et al., 2005; Paul and Meyer, 2008; Hughes et al., 2014b). Our physical habitat data indicate that the interventions only resulted in improvement from impaired to altered—but well below reference condition (Callisto et al., 2002). It is noteworthy that some parameters related to the surroundings or the hydrological regime could not undergo major recovery because of the characteristics of consolidated urban areas (Hughes et al., 2014b; Loflen et al., 2016) and the markedly greater time usually required for recovering physical-habitat and flow-regime (which was not considered) than for water quality recovery (Hughes et al., 2014b).

4.3 Macroinvertebrate assemblage condition

Both physical habitat and water quality rehabilitation occurred to a greater degree than biological rehabilitation—which did not approach reference conditions–as has been reported by others (Charbonneau and Resh, 1992; Selvakumar et al., 2010; Kail et al., 2015; Macedo and Magalhães Jr., 2020). We observed improved macroinvertebrate assemblage composition and MMI scores over time, but we cannot state whether further improvement in biological conditions are possible because the urban catchments and migration/colonization barriers limit biological processes and MMI scores (Bond and Lake, 2003; Angold et al., 2006). Nonetheless, we found that use of an MMI, which combines and quantifies multiple measures of assemblage condition into a single indicator, provided a useful and easily communicated tool for expressing biological monitoring results over time as reported by Vadas et al. (2022). In addition, MMI scores closely tracked the physical habitat index scores (Figure 5), suggesting that further improvements in the latter may be more effective than further improvements in water quality. Our results also were similar to several other studies dealing with urban rehabilitation projects in Global North countries, which showed varied biological results, with only 5%–20% showing significant biological improvements (Al-Zankana et al., 2020). Those results were not always revealed by richness and diversity indices, rather, they were shown by relative abundances or taxonomic composition (Palmer et al., 2014; Kail et al., 2015). This expectation of varied responses reinforces the need to use multimetric indices in the evaluation of rehabilitation projects, because they present the response of multiple attributes of assemblages (Callisto et al., 2022). Regarding our family level identification, in the Neotropics, it is usually the highest possible taxonomic resolution to be achieved for many taxa, because of the huge biodiversity and limited taxonomic knowledge for most groups (Helson and Williams, 2013). Even when identification to a finer level is possible, it is often too work-intensive to be used in biomonitoring programs (Martins et al., 2022). In fact, many studies have shown that family level identification is able to attain the same accuracy as lower taxonomic level identifications in both biomonitoring and ecological studies (Bailey et al., 2001; Buss and Vitorino, 2010; Silva et al., 2016).

4.4 Citizen perceptions

Although ecological conditions were not restored to natural conditions, we found that the interventions, especially the installation of riparian parks and sewage treatment, were viewed positively by citizens neighboring the stream sites. Furthermore, the results indicated that those people favored those options over stream burial, which is widely employed in large Brazilian cities. This indicates that those rehabilitation options can provide important ecosystem services, in addition to improving ecological and biological conditions (Ranta et al., 2021). Because the three stream sites had similar sociodemographic characteristics, we analyzed the data from the surroundings of the three urban parks together.

Despite being widely neglected in the evaluation of rehabilitation projects (Guida-Johnson and Zuleta, 2017), citizen perceptions are vitally important because they reveal taxpayer support or opposition regarding intervention operations over time (Bernhardt and Palmer, 2007). Furthermore, citizen support for ecosystem services stimulates more interventions of particular types. In Global North countries, wastewater infrastructure has been widely implemented (da Silva and Porto, 2021); but in Brazil industrial and municipal wastewater pollution is widespread in urban areas. Therefore, wastewater treatment was initially the most pertinent intervention for the local Belo Horizonte population, but subsequently parks became the preferred intervention.

4.5 Ecosystem services and management

Rehabilitated streams also showed improvement in the provision of ecosystem services in urban areas (Ranta et al., 2021). The creation of parks provides public use for recreation, which clearly provides cultural services related to mental and physical health and environmental education (Zhang et al., 2017). In addition, the rehabilitation of the floodplain-streambed system improves infiltration conditions, aquifer recharge and sediment and flood control (Mould and Fryirs, 2018), a fact perceived by the local citizen population. The current water quality could provide the service of public supply through simple treatment, even if in practice the quantity of water does not allow the feasibility of an action like this.

Our study reinforces the need for long-term monitoring of rehabilitation actions, which despite its importance, represents a major gap in rehabilitation projects (Hughes et al., 2014a,b; Al-Zankana et al., 2020; dos Reis Oliveira et al., 2020). It is also important to note that legislation has been a major motivator for environmental rehabilitation globally (Feio et al., 2021). Brazil has environmental laws that protect riparian vegetation (Brazil, 2012) and chemical and physical water quality standards for rivers, streams and lakes (Brazil, 2005), but neither mandates the rehabilitation of freshwater biological conditions. Considering the high monetary value of urban land, rehabilitation interventions are a great challenge, so legal instruments that encourage protecting, rehabilitating, and monitoring streams are essential (da Silva and Porto, 2021).

5 Conclusion

Over the past 10+ years since the rehabilitation measures were implemented, the sites have remained in markedly better ecological condition, including persistence following annual freshets. Nonetheless, we expect that periodic monitoring and maintenance measures must be employed to ensure rehabilitation effectiveness and persistence. Continued communication with local landowners will be critical for meeting these concerns.

This study contributes data and critical multi-tool information about the relevance of environmental rehabilitation of stream sites in the third largest Brazilian metropolis. We hope these results support more appropriate options for managing urban streams in the Global South than hardening, channelization, and burial. As shown, linear riparian parks and sewage collection and treatment not only offer multiple ecosystem services for human beings, they also improve ecological and biological conditions of urban streams.

Future studies might explore three additional avenues. (1) We could evaluate the three stream sites separately to determine possible differences in degrees of recovery considering the pre rehabilitation condition. (2) It could be useful to determine whether rehabilitated streams in Brazilian urban areas can provide ecosystem services comparable to other urban protected areas without a history of substantial degradation. (3) We should use functional ecosystem processes (e.g., primary production, leaf breakdown, sediment transportation and deposition, benthic bioindicators functional diversity indices), to assess the recovery process of urban streams along a gradient of anthropogenic disturbance.

Data availability statement

The datasets presented in this study can be found in online repositories. The name of the repository and accession number can be found below: https://doi.org/10.5281/zenodo.6465160.

Ethics statement

The studies involving human participants were reviewed and approved by Universidade Federal de Minas Gerais' research ethics committee (COEP-UFMG). The participants provided their written informed consent to participate in this study.

Author contributions

DRM and MC conceived the study. DRM, MC, BMLR, MR-N, and JSS conducted field work. DRM, MC, MSL, BMLR, MR-N, and JSS performed the analyses. DRM wrote the manuscript with contributions from MC, MSL, and RMH. All authors reviewed the manuscript and approved the final version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.921934/full#supplementary-material

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