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Threats to the integrity of urban streams in the southwest amazon

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ABSTRACT

This study characterized the physical integrity, hydromorphology, and limnology of ten urban streams in the Southwestern Amazon. The objective was to investigate how these characteristics covary and identify threats to the health of these ecosystems. The physical integrity of the streams was assessed using a Habitat Integrity Index (HII), hydromorphology based on width, depth, flow, and substrate type, and limnological characterization through 14 physico-chemical parameters during dry and rainy seasons. Three streams were classified as preserved, two as intermediate, and five as degraded. Anthropogenic alterations were observed in hydromorphological characteristics, especially in width, depth, and substrate type across different integrity categories. Limnological analysis revealed that chemical and biochemical oxygen demands, ammoniacal nitrogen, nitrate, dissolved iron, and sulfides exceeded the limits established by Brazilian water quality regulations (CONAMA 357/2005). The alteration of these parameters reveals that the primary threat to the integrity of these ecosystems is sewage collection and treatment issues, reflecting the absence of basic sanitation. Redundancy Analysis (RDA) indicated the influence of specific substrate types on parameters in degraded streams, while preserved streams showed a correlation between dissolved oxygen with riparian forest conditions and the absence of anthropogenic influence. Cluster analysis emphasized the importance of integrating environmental, hydromorphological, and limnological metrics for a comprehensive assessment of ecosystem health. Given the heterogeneity of Amazonian aquatic ecosystems, this study may contribute to the establishment of criteria based on regional characteristics for accurate assessment and guidance of public policies aimed at protecting and ensuring the integrity of these ecosystems.

Keywords: limnological characteristics, microbiological analysis, Porto Velho, urbanization.

Ameaças à integridade dos córregos urbanos na Amazônia Sul-Ocidental

RESUMO

Neste estudo, caracterizamos a integridade física, hidromorfologia e limnologia de dez igarapés urbanos da Amazônia Sul-Ocidental com diferentes graus de antropização, com o objetivo de investigar como essas características covariam e identificar as ameaças à saúde desses ecossistemas. A integridade física dos igarapés foi avaliada por um Índice de Integridade de Habitat (HII), a hidromorfologia com base na largura, profundidade, vazão e tipo de substrato, e a caracterização limnológica através de 14 parâmetros físico-químicos durante as estações seca e chuvosa. Três igarapés foram classificados como preservados, dois como intermediários e cinco como degradados. Alterações antrópicas foram observadas nas características hidromorfológicas, principalmente na largura, profundidade e tipo de substrato em diferentes categorias de integridade. A análise limnológica revelou que as demandas químicas e bioquímicas de oxigênio dissolvido, nitrogênio amoniacal, nitrato, ferro dissolvido e sulfetos ultrapassaram os limites estabelecidos pela regulamentação brasileira de qualidade da água (CONAMA 357/2005). A Análise de Redundância (RDA) indicou a influência de tipos específicos de substrato nos parâmetros dos igarapés degradados, enquanto os igarapés preservados mostraram correlação entre o oxigênio dissolvido e as condições da mata ciliar. A análise de cluster enfatizou a importância da integração de métricas ambientais, hidromorfológicas e limnológicas para uma avaliação abrangente da saúde do ecossistema. Dada a heterogeneidade dos ecossistemas aquáticos amazônicos, este estudo poderá contribuir para o estabelecimento de critérios baseados em características regionais para avaliação precisa e orientação de políticas públicas que visem proteger e garantir a integridade desses ecossistemas.

Palavras-chave: análise microbiológica, características limnológicas, Porto Velho, urbanização.

1. INTRODUCTION

The Amazon Basin is the most extensive hydrographic network on the planet, composed of rivers, lakes, and streams distributed over a wide geographical area. The landscape's heterogeneity plays a crucial role in determining the limnological, biological, and environmental characteristics of this complex ecosystem (Fang *et al.*, 2017; Junk *et al.*, 1989; Milliken *et al.*, 2010; Ríos-Villamizar *et al.*, 2020). The combination of these characteristics provides essential services (Fu *et al.*, 2013; Longo and Rodrigues, 2017), such as water, food, herbal remedies, energy, cultural relationships, and livelihoods for the human populations that have settled in the region (Fish *et al.*, 2016; Sancho-Pivoto *et al.*, 2022). Consequently, aquatic ecosystem preservation is crucial for ensuring the quality of life for these populations and the stability and sustainability of ecosystems.

However, over the past 20 years, the intensity of anthropogenic activities associated with urbanization has created a scenario of environmental degradation for Amazonian aquatic ecosystems (Davidson *et al.*, 2012; Foley *et al.*, 2007). This degradation predominantly occurs in urban areas due to increased deforestation, improper waste disposal, discharge of domestic and industrial effluents, pollution (Cabrera *et al.*, 2023; Saviato *et al.*, 2022), and other severe modifications to the natural characteristics of these ecosystems. Such modifications compromise environmental quality, water availability, and quality (Ferreira *et al.*, 2021), as well as the health of human and animal users of these resources (Confalonieri, 2000). These environmental changes are frequently observed in stream ecosystems, especially those located in urban areas (Beltrão *et al.*, 2018; Couceiro *et al.*, 2007; Ferreira *et al.*, 2021; Santos *et al.*, 2020), where population density is higher, and these watercourses are often transformed into open sewers.

Streams play a crucial role in maintaining water balance in adjacent ecosystems, while also offering a variety of habitats that harbor a diverse and unique biodiversity (Ferreira *et al.*, 2023; Leal *et al.*, 2016). In urban areas, their importance extends to drainage and flood control, helping to reduce the risks of inundation (Rowiński *et al.*, 2018). Furthermore, amidst various threats arising from anthropogenic pressure in urbanized areas, the importance of these ecosystems is even more evident (Kühl *et al.*, 2010; Ranta *et al.*, 2021), as they constitute green areas within cities, providing natural spaces for leisure, recreation, and contributing to improved air quality (Vieira *et al.*, 2018; Higgins *et al.*, 2019). By providing people with direct contact with nature in urban environments, streams also play a significant role in promoting quality of life (Higgins *et al.*, 2019).

Understanding of the health of urban Amazonian stream ecosystems, types of threats, and their effects on health and diversity has been increasingly investigated, revealing that they are under constant threat (e.g., Casatti *et al.*, 2006; Couceiro *et al.*, 2007; Resende *et al.*, 2021; Ferreira *et al.*, 2021; Martins *et al.*, 2017; Monteiro-Júnior *et al.*, 2014; Oliveira *et al.*, 2017; Oliveira-Junior *et al.*, 2019; Santos *et al.*, 2020). However, in the Southwestern Amazon, knowledge of the main factors threatening their integrity and associated impacts is still in its early stages. The city of Porto Velho (the third municipality with the largest population in the Northern region of Brazil; IBGE 2020), faces constant changes with the advancement of agropastoral activities, deforestation, pollution, and other transformations, especially in urban areas due to deficiencies in basic sanitation (Cardille and Foley, 2003; Moreira da Silva *et al.*, 2005).

Generating information about the physical and chemical characteristics of water, structural features, and environmental integrity conditions of streams in this region is crucial for assessing the effects of these changes on urban aquatic ecosystems over the years (Fu *et al.*, 2013). Maintaining the natural characteristics of these ecosystems is essential for preserving aquatic biota, which requires specific features for reproduction, growth, migration, and performing their functions in the ecosystem (Henle *et al.*, 2004). This preservation is not only important for the health and well-being of aquatic organisms, but also for the health and well-being of human populations (Confalonieri, 2000; Fu *et al.*, 2013). Therefore, this knowledge contributes to guiding mitigative measures and formulating public policies tailored to regional specificities (Monte *et al.*, 2021).

This study characterized the physical integrity, hydromorphology, and limnology of ten urban streams in the Southwestern Amazon, with varying degrees of anthropization. The aim was to identify threats to the health of these ecosystems and investigate how limnological characteristics covary with the locations and their environmental and hydromorphological features. We hypothesize that urban streams in Southwest Amazonia with higher degrees of anthropogenic influence exhibit higher levels of physical and limnological degradation.

2. MATERIAL AND METHODS

2.1. Study Area and Collection Points

The study was conducted in the city of Porto Velho, the capital of the state of Rondônia, located in the northern region of Brazil (Figure 1). Its urban delimitation covers approximately 118,960 km² and houses a population of 460,434 inhabitants throughout its territory area, making it the most populous municipality in the state (IBGE, 2022). The predominant climate is tropical superhumid, characterized by being very hot (average annual temperature of 25.6ºC) and having high humidity throughout the year, with averages above 80%. The dry season occurs between July and September, while the wet season occurs from January to March.

The city is drained by tributaries on the right bank of the Madeira River, the second-largest tributary of the Amazon River. These tributaries are distributed across 5 micro basins - Igarapé

Grande, Igarapé dos Tanques, Igarapé Tancredo Neves, Belmont, and Bate Estacas (Silva, 2020). A significant portion of the streams that make up this city's hydrographic network is vulnerable to the effects of urbanization, which increases anthropogenic pressure on these ecosystems. This leads to the disorderly occupation of areas, an increase in pollutant sources, and the loss of surrounding vegetation.

For this study, ten streams were selected, with seven located in the urban perimeter under anthropogenic influence and three in peri-urban areas with lower anthropogenic pressure (Fig. 1; Table 1). The selection of these points was carried out using satellite images on Google Earth, followed by on-site visits to verify accessibility and confirm that the area was suitable for the application of the collection protocol.

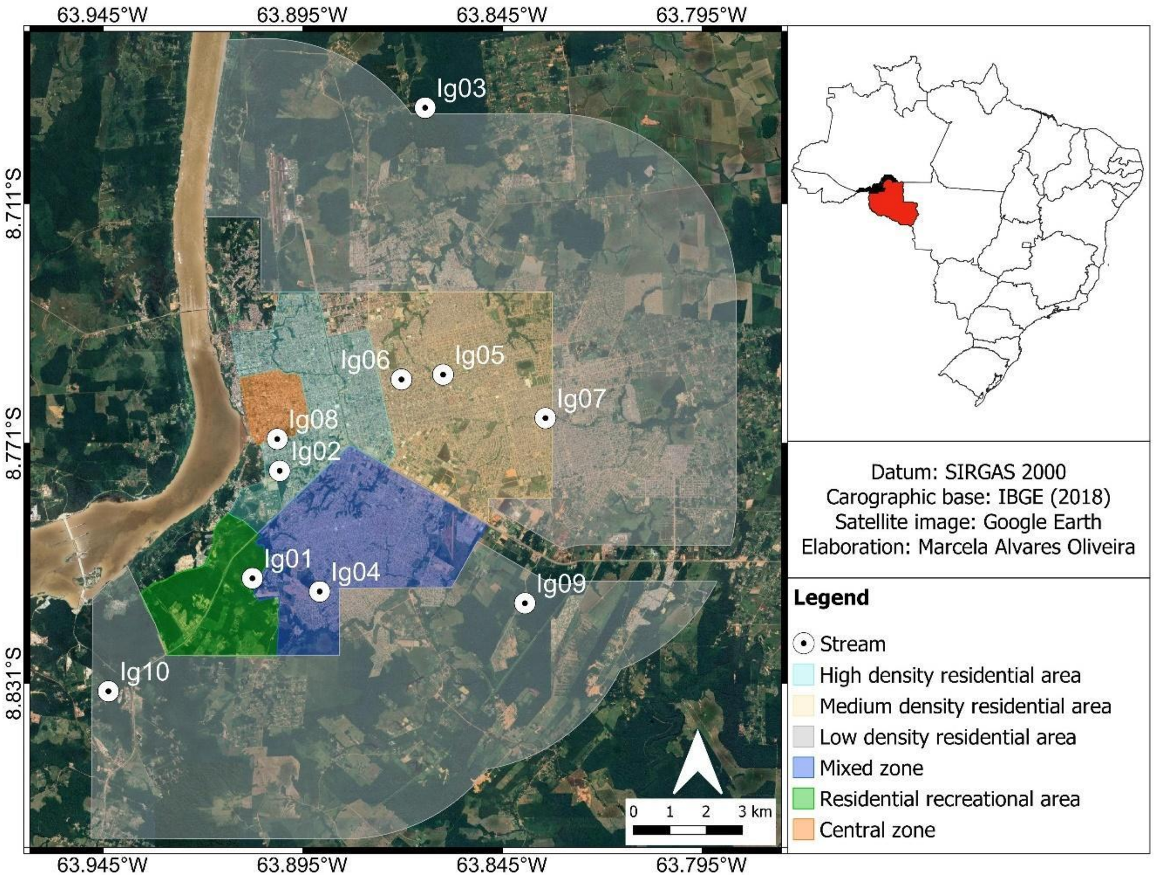

Figure 1. Study area and distribution of sampling points.

2.2. Data Collection

For data collection, a sampling unit of 100 meters was established in each stream. Subsequently, five markings were made at points 0m, 25m, 50m, 75m, and 100m, in the downstream-upstream direction, following Continental Aquatic Subprogram for Streams protocols, established by the federal environmental agency (Instituto Chico Mendes - ICMBio), called National Biodiversity Monitoring Program (Monitora) (Dantas *et al.*, 2022). Sampling was conducted during the dry and wet seasons, considering the most significant hydrological periods for Amazonian aquatic ecosystems (Junk *et al.*, 1989), in March-April and August-September of the year 2022, respectively.

Table 1. Location data and characteristics of collection points.

Stream code	Micro-basin	Area	Latitude	Longitude	Characteristics of the studied excerpt
Ig01	Bate Estaca Stream	Urban	-8,804731	-63,907608	Left bank of the stream: few residences; domestic sewage disposal; garbage in the surrounding area and in the stream. Right bank: belongs to an Army Protection Area, absence of residences, medium-sized vegetation with an average height of 10m, strong presence of pioneer species. Close to an area of rural properties with small and medium size farms.
Ig02	Grande Stream	Urban	-8,777872	-63,900783	Many residences on both banks; garbage in the surrounding area and in the stream; dumping of domestic sewage, nearby gas stations and car washes; vegetation marked by large open areas where tree vegetation is discontinuous. Presence of individuals of exotic species and extensive graminoid stratum. Low floristic diversity.
Ig03	Belmont Stream	Periurban	-8,687056	-63,864361	Located inside a municipal conservation unit. Absence of residences, sewage, and garbage discharges. Huge area with well-preserved vegetation and high specific diversity.
Ig04	Bate estaca Stream	Urban	-8,808041	-63,890761	Many residences on both banks; domestic sewage disposal; garbage in and around the stream. Presence of extensive graminoid stratum. Low floristic diversity.
Ig05	Belmont Stream	Urban	-8,755018	-63,870291	Many residences on both banks, being larger on the right bank; the arboreal vegetation is discontinuous. Presence of individuals of exotic species. Presence of extensive graminoid stratum.
Ig06	Belmont Stream	Urban	-8,756044	-63,859701	Located within an environmental protection area; many residences in the surrounding area but absent on the banks; evidence of domestic and industrial sewage; presence of individuals of exotic species and extensive graminoid stratum. Low floristic diversity.
Ig07	Tancredo Neves Stream	Urban	-8,764679	-63,834249	Many residences on both banks; excess discharge of domestic and commercial sewage. Presence of extensive graminoid stratum. Low floristic diversity.
Ig08	Grande Stream	Urban	-8,769907	-63,901383	Right bank with many residences; left bank a Municipal park. Discharge of domestic sewage on both banks; presence of a gas station and car wash nearby. Presence of extensive graminoid stratum. Low floristic diversity.
Ig09	Garças River	Periurban	-8,810971	-63,839371	Located in a little altered permanent preservation area. Absence of residences on both banks and sewage discharges; presence of waste in low quantities. Vegetation with an average height of 12m, important presence of pioneer species.
Ig10	Bate estaca Stream	Periurban	-8,833167	-63,943667	Permanent preservation area present, but altered, rural property area – small and medium size farms, receives effluents from the municipal landfill upstream of the sampled section, vegetation with an average height of 13m and high specific richness.

For the assessment of environmental integrity, the streams were characterized based on observed features related to residential density, discharge of domestic and/or commercial effluents, and the type of vegetation and influences in their surroundings. The environmental conditions of the studied sections were evaluated using a version of the Habitat Integrity Index (HII), adapted by Monteiro-Júnior *et al.* (2014), for urban environments. The index comprises 12 metrics, including access to the stream, width, and integrity of the riparian forest, vegetation within 10 meters of the channel, retention devices, channel structure, water flow in the channel, canopy cover (calculated by: ratio of black pixel area in monochromatic canopy images to the total number of pixels), absence of human occupation, absence of domestic or industrial effluents, absence of construction density, and absence of dumped litter. The assessment provides a final score ranging from 0 to 1. Consequently, the streams were classified into three integrity categories based on their scores: scores below 0.33 were considered degraded; scores between 0.34 and 0.66 were considered intermediate, and scores above 0.67 were considered preserved.

The hydromorphological characterization was carried out by measuring the following parameters at each point of the sampling unit: width (m), depth (cm), current flow velocity (m/s), discharge (m^3/s), and substrate type. The width was measured using a tape measure. Depth was obtained from five vertical sections at each point using a measuring tape. Current flow velocity was measured based on the travel time of a floating object over a distance of 1 meter. Discharge was calculated using the equation Q=A.Vm, where Q is the discharge; A is the cross-sectional area, and Vm is the average water flow velocity. The substrate type was determined based on the predominant material at the stream bottom, categorized as: sand, clay, leaf litter, aquatic plants, stone, root, trunk, and mud.

Measurements of 14 physicochemical water parameters were obtained for limnological characterization (Table 2). Among these, temperature (ºC), pH, turbidity (NTU), electrical conductivity (mS/cm), and dissolved oxygen (mg/L) were measured in situ using a multiparameter probe AQUAREAD AP-2000 at the five points of the sampling unit, and the average was calculated. For the remaining parameters, 500ml water samples were collected at a single central point and transported in a styrofoam container to the Commercial Water Analysis Laboratory of Aparício Carvalho University Center - FIMCA, by a responsible technician, using Alfakit Bench Unikits adapted from the Standard Methods for the Examination of Water and Wastewater 23rd edition. The results were evaluated concerning CONAMA Resolution 357/2005 (CONAMA, 2005).

Table 2. List of physicochemical parameters analyzed.

Limnological parameters	Abbreviation	Unit
Hidrogenionic potential	pH	-
Electrical Conductivity	EC	mS/cm^{-1}
Temperature	TP	ºC
Dissolved oxygen	DO	mg/L
Turbidity	TB	NTU
Total ammonia nitrogen	NH_4^+	mg/L N
Chloridae	Cl	mg/L Cl
Dissolved iron	FeD	mg/L Fe
Chemical oxygen demand	COD	mg/L O^2
Biochemical oxygen demand	BOD	mg/L O^3
Nitrate	NO_3^-	mg/L N
Nitrite	NO_2^-	mg/L N
Sulfate	SO_4^{2-}	mg/L SO_4
Sulfide	H_2S	mg/L S

The water quality analysis aimed to detect the presence or absence of total and fecal coliforms. In the Microbiology laboratory of the Oswaldo Cruz Foundation – Rondônia, the qualitative test was performed on 100ml water samples using the Colitag^{TM} medium, following the methodology of the Standard Methods for the Examination of Water and Wastewater, and the manufacturer's instructions were followed.

2.3. Data Analysis

The data were organized into spreadsheets using Microsoft Excel software, where statistical descriptors such as mean and standard deviation were calculated to summarize the results of the limnological and structural characterization of the streams.

The limnological dataset was subjected to Principal Component Analysis (PCA) to identify predictor variables and how the sampled points cluster in relation to these variables. For this analysis, data normalization was conducted using the Z-score method, which entails subtracting the mean of each variable and dividing by its respective standard deviation. This approach serves to mitigate differences and the influence of extreme values resulting from scale variations among the analyzed variables. To investigate how limnological characteristics covary with the sites and their environmental and hydromorphological characteristics, Redundancy Analysis (RDA) was performed, with limnological and hydromorphological data as dependent variables and HII index metric scores as independent variables. Finally, a hierarchical cluster analysis using the Unweighted Pair-Group Average (UPGMA) method was conducted, using Euclidean distance as the dissimilarity measure, to assess the similarity of points regarding the analyzed dataset. For RDA and cluster analysis, only dry season data were used, as it is the seasonal period that best represents the characteristics of Amazonian streams. These analyses were executed in R, Version 4.2.3.

3. RESULTS AND DISCUSSION

The results highlighted distinct environmental, hydromorphological, and limnological characteristics between the streams located in the urban perimeter and those in the peri-urban area. In urban streams, features indicative of degradation predominate, demonstrating that water bodies in the Southwestern Amazon have also experienced the effects of urbanization associated with population growth and disorderly occupation. Streams in the peri-urban area indicate environments with preserved natural characteristics but are threatened by fertilizer use in agro-pastoral activities. The altered parameters reveal that the main threat to the integrity of these ecosystems is sewage collection and treatment issues, reflecting the lack of basic sanitation in the municipality, which ranks among the worst nationally (Oliveira *et al.*, 2023). Similar observations have also been made in other regions of the Brazilian Amazon, in cities such as Manaus, Rio Branco, Tocantins, Paragominas, and Santarém (Araujo *et al.*, 2020; Couceiro *et al.*, 2007; Ferreira *et al.*, 2012; 2021; Figueiredo *et al.*, 2010; Santos *et al.*, 2020; Saviato *et al.*, 2022).

3.1. Environmental Integrity

As HII scores ranged from 0.14 in Ig06 to 0.88 in Ig03. The three peri-urban streams (Ig03, Ig09, and Ig10) were classified as preserved with scores of 0.88, 0.68, and 0.69, respectively (Table 1). Regarding urban streams, two were classified as intermediate (Ig01 and Ig02; HII=0.34), and five were classified as degraded, with HII scores ranging from 0.14 to 0.22.

The Habitat Index of Streams (HII) assesses features such as vegetation conditions along streambanks, human occupation, effluent discharge, and presence of litter (Monteiro-Junior *et al.*, 2014). The results obtained through the HII accurately reflected these characteristics in each stream, demonstrating the index's effectiveness in characterizing habitat physical structure, as also evidenced in other studies (Brasil *et al.*, 2020; Giehl *et al.*, 2019; Monteiro-Junior *et al.*, 2014; 2015; Silva-Santos *et al.*, 2023).

In preserved streams, the preservation of riparian vegetation on both banks and a lesser influence of human occupation characteristics contributed to higher scores. Conversely, degraded streams showed lower scores due to the presence of characteristics related to occupation, such as absent vegetation along the banks, litter presence in the streambed and surroundings, and effluent discharges. This trend was also observed in other studies employing the HII (e.g., Giehl *et al.*, 2019; Monteiro-Junior *et al.*, 2014; 2015; Silva-Santos *et al.*, 2023).

The intermediate streams, despite experiencing urbanization effects, still retain some environmental characteristics, such as vegetation presence on at least one bank. However, signs of human occupation, especially litter presence, are also evident, resulting in scores close to the minimum value for this classification.

3.2. Hydromorphological Characterization

Hydromorphological characteristics distinguished the preserved streams from the intermediate and degraded ones. The width ranged from 1 meter in Ig03 to 8.75 meters in Ig06, being greater in degraded streams and smaller in preserved ones. The depth varied from 0.11 to 0.31 meters in streams Ig05 and Ig09, respectively, and was greater in intermediate streams, as was the flow, which was higher in Ig02 (0.69 m^3/s) and lower in Ig05 (0.02 m^3/s). Regarding substrate type, the predominant material in preserved streams was leaf litter (40.7%), while sand predominated in intermediate streams (43%), and in degraded ones, mud (29.2%).

In the urban area, the hydromorphology of the streams is affected by the types of land use and occupation in the surrounding areas, as well as other anthropogenic activities of varying magnitudes, similar to those assessed by the HII, which can result in the alteration of their structural characteristics. During the sampling period, it was possible to observe streambed filling or diversion to meet the demands of construction, damming for fish farming, and dredging activities in the studied streams. Notably, dredging is a public initiative outlined in the municipality's basic sanitation plan, considered a cleaning action for urban streams. Excavators are used to clear channels, remove deposited material from the bed, and eliminate vegetation and soil from the riverine banks. This action results in widening, increased depth, and removal of the original substrate of these systems. Our results reveal the effects of these anthropogenic alterations on the hydro-morphology of the streams in the urban area sampled in this study.

Changes in these characteristics can affect ecosystem stability and impact the biological communities inhabiting them. This is because it reduces the availability of microhabitats and food, promotes landscape homogenization, affecting aquatic biota primarily composed of tolerant species (Henle *et al.*, 2004; Miguel *et al.*, 2017; Ortega *et al.*, 2021).

3.3. Limnological characteristics

The limnological characteristics among preserved, intermediate, and degraded streams indicated that water quality, as well as pollution levels and sources, differ among the sampled points. These differences can be observed in both the average values of the variables at each point (Table 3) and in the results of the PCA (Figure 2). In preserved streams, the averages of pH, EC, TP, TB, NH_4^+, Cl, BOD, and SO_4^{2-} were lower in both seasonal periods, while the averages of DO and NO3- were higher. On the other hand, in the degraded streams, the average values of EC, TP, TB, Cl, COD, BOD, SO_4^2 were higher in both seasonal periods, as well as the average values of DO, NO_3^- and H_2S, which were low. Concerning intermediate streams, higher averages were observed only for the Cl variable in both seasonal periods, with elevated averages of pH, NH_4^+, FeD, NO_2^- e H_2S during the flood period, while during the dry season were FeD e COD (Table 3). The PCA, with the first two axes explaining 48.3% of the variance, indicated that EC contributed most to the variance in the first axis, with degraded streams being more associated during the dry period, while in the second axis, H2S and TB were the variables to which degraded streams were more related during the flood period (Figure 2).

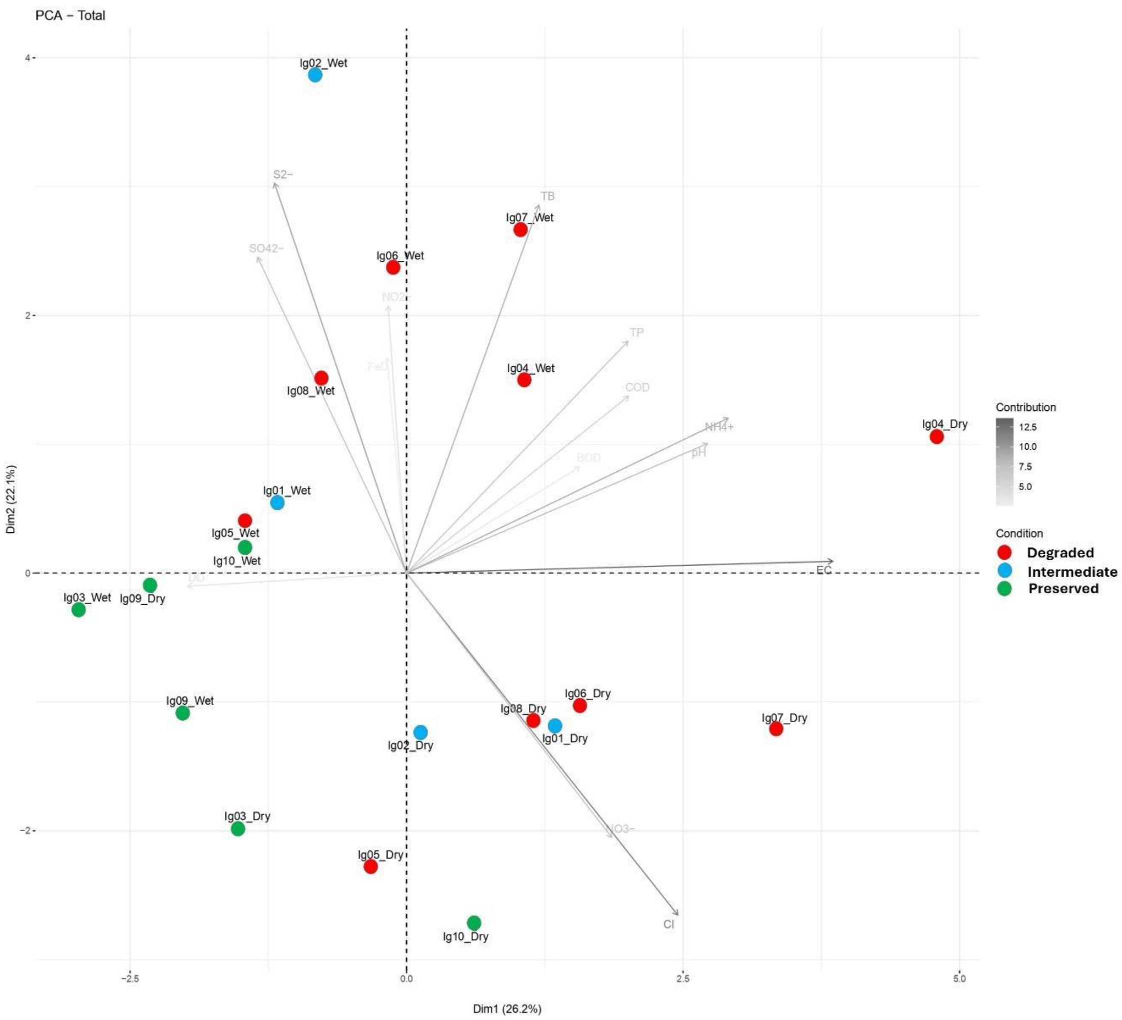

Figure 2. Results of the Principal Component Analysis (PCA) with limnological variables considering the flood and dry periods.

Similar results have also been observed in other studies involving Amazonian streams, where associations were made with different levels of integrity or anthropization (Cunha *et al.*, 2022; Silva-Santos *et al.*, 2023). Streams located in more preserved areas had their waters characterized as acidic, with good oxygenation, low electrical conductivity, slightly turbid, and mild temperatures. In contrast, urban streams exhibited alkaline waters, turbidity, elevated conductivity and temperature, and low oxygenation (e.g., Barros *et al.*, 2020; Beltrão *et al.*, 2018; Ferreira *et al.*, 2012; 2021; Santos *et al.*, 2020). These characteristics reflect the natural or non-natural specifics of each environment, their physical integrity, and levels of anthropization (Clément *et al.*, 2017). They are primarily related to soil characteristics and the presence of continuous tree vegetation in the surroundings, which provides organic matter (Monte *et al.*, 2021; Wasserman *et al.*, 2019). In contrast, in urban areas, soil characteristics are altered, tree vegetation is discontinuous and often absent, and organic matter originates from anthropogenic sources (Cunha *et al.*, 2022; Martins *et al.*, 2017).

Table 3. Limnological Characteristics of Urban and Periurban Streams in Porto Velho, Rondônia, Brazil. *Indicates values that exceeded the limits established by CONAMA Resolution 357/2005.

Limnological parameters	Seasonal period	Stream												
		Preserved				Intermediate			Degraded					
		Ig03	Ig09	Ig10	*Mean*	Ig01	Ig02	*Mean*	Ig04	Ig05	Ig06	Ig07	Ig08	*Mean*
Ph	Wet	6.10	7.54	7.10	6.91	7.00	7.76	7.38	7.83	6.58	6.72	7.46	7.12	7.14
	Dry	6.74	6.68	6.60	6.67	7.14	7.48	7.31	8.12	7.18	7.64	8.02	6.82	7.56
EC	Wet	0.01	0.02	0.17	0.07	0.15	0.17	0.16	0.29	0.16	0.25	0.34	0.19	0.25
	Dry	0.02	0.01	0.35	0.13	0.34	0.28	0.31	0.65	0.23	0.46	0.53	0.22	0.42
TP	Wet	25.04	23.58	26.18	24.93	26.90	27.72	27.31	34.00	29.04	29.60	30.20	27.40	30.05
	Dry	24.20	25.40	25.18	24.93	28.20	27.54	27.87	26.78	24.86	29.50	30.54	28.70	28.08
TB	Wet	0.00	3.91	1.93	1.95	7.13	61.69	34.41	39.40	11.40	16.80	62.30	65.60	39.10
	Dry	0.00	9.90	3.90	4.60	10.30	14.80	12.55	25.70	8.10	17.30	36.40	4.09	18.32
DO	Wet	5.65	6.20	5.70	5.85	4.30*	4.90*	4.60	5.43	6.72	5.38	5.18	5.06	5.55
	Dry	5.36	6.66	5.60	5.87	5.70	5.50	5.60	4.80*	5.20	4.66*	4.47*	2.90*	4.41
COD	Wet	72.00*	56.00*	88.00*	72.00	284.00*	68.00*	176.00	118.20*	609.00*	780.00*	800.00*	66.00*	474.64
	Dry	284.99*	232.40*	184.48*	233.96	331.26*	88.22	209.74	1990.00*	20.70	3.68	77.41*	3.89	419.14
BOD	Wet	19.00*	14.80*	11.00*	14.93	120.00*	20.00*	70.00	82.80*	460.00*	516.00*	510.00*	33.00*	320.36
	Dry	131.14*	38.66*	29.14*	66.31	132.64*	42.84*	87.74	461.50*	19.50*	414.40*	35.03*	804.80*	347.05
Cl	Wet	0.40	0.30	0.60	0.43	0.40	0.50	0.45	0.40	0.40	0.40	0.30	0.40	0.38
	Dry	28.40	21.30	56.80	35.50	56.80	49.70	53.25	48.90	35.50	35.50	49.70	42.60	42.44
FeD	Wet	0.39*	0.66*	0.65*	0.57	1.90*	2.81*	2.36	1.55*	0.57*	0.81*	1.63*	1.17*	1.15
	Dry	0.37*	5.52*	0.74*	2.21	1.00*	0.38*	0.69	2.61*	0.23	0.10	0.89*	0.38*	0.84
NH_4^+	Wet	0.50	0.21	1.57	0.76	0.56	1.87	1.22	1.96	0.07	1.78	1.11	0.81	1.15
	Dry	0.12	0.02	1.70	0.61	2.43	0.12	1.28	6.00*	0.02	0.12	2.04*	0.88	1.81
NO_3^-	Wet	0.21	0.01	0.26	0.16	0.16	0.20	0.18	0.13	0.30	0.43	0.19	0.19	0.25
	Dry	0.12	1.94	22.90*	8.32	11.60*	1.12	6.36	0.86	13.80*	9.50	35.03*	2.08	12.25
NO_2^-	Wet	0.16	0.03	0.08	0.09	0.08	0.12	0.10	0.12	0.01	0.48	0.21	0.09	0.18
	Dry	0.02	0.02	0.02	0.02	0.20	0.07	0.14	0.01	0.01	0.06	0.02	0.06	0.03
SO_4^{2-}	Wet	23.10	11.66	26.12	20.29	32.97	37.30	35.14	0.30	33.70	27.37	13.94	22.51	19.56
	Dry	0.12	4.75	6.94	3.94	3.48	11.54	7.51	12.14	2.23	8.57	9.72	9.15	8.36
H_2S	Wet	0.10*	0.02*	0.09*	0.07	0.05*	0.35*	0.20	0.10*	0.02*	0.09*	0.13*	0.10*	0.09
	Dry	0.03*	0.12*	0.00	0.05	0.00	0.01*	0.01	0.01*	0.04*	0.01*	0.03*	0.00	0.02

The average values of some variables exceeded the limits established by CONAMA Resolution 357/2005, governing water quality in Brazil. This was observed mainly in degraded and intermediate streams, but also in one preserved stream. Among these variables are the availability of DO, which was low in intermediate and degraded streams, except for Ig05, and the values of BOD and COD that exceeded the maximum allowed limit in all streams. DO is one of the most crucial parameters for maintaining aquatic life forms and can result in the mortality of several aquatic species. The low availability of DO in the environment, as mentioned in the resolution, may be associated with various factors such as the discharge of domestic sewage, observed in all intermediate and degraded streams in this study. In addition, improper waste disposal leads to the accumulation of organic matter and uncontrolled bacterial growth, confirmed by high values of COD and BOD.

The average values of hydrogen sulfide H_2S also exceeded the maximum limit in all streams, with the highest concentration observed in Ig07. In surface waters, sulfide contamination can be linked to both natural factors, justifying alterations in preserved streams, and anthropogenic activities. This contamination may occur due to the reduction of sulfates under conditions of low DO availability or the decomposition of organic matter in the water body substrate (Fedorov *et al.*, 2019). In forested areas of the Amazon, the substrate composition of streams includes a significant amount of organic matter, such as leaves, roots, and tree trunks from the surrounding forest (Ferreira *et al.*, 2021; Beltrão *et al.*, 2018; Mendonça *et al.*, 2005). This was also observed in the preserved streams of this study and may be associated with changes in this parameter. On the other hand, in intermediate and degraded streams, the substrate consisted of muddy sediment with a strong odor, attributed to improper waste disposal and the discharge of domestic effluents in these stream areas. This highlights their source of anthropogenic organic matter.

Another altered parameter was FeD, in all sampled streams. Ig03, the most intact of those evaluated, showed average values closer to the maximum limit established by current legislation in both seasonal periods. On the other hand, Ig09, also classified as preserved, presented the highest average value. This is a variable that can be influenced mainly by the type of soil, which in the study area is predominantly red-yellow argisols rich in iron oxide, and may be the main cause of the alteration in concentrations of this element in these streams (Shinzato *et al.*, 2010). However, in intermediate and degraded streams, exposure to various types of polluting sources and other effects of urbanization can also lead to changes in this parameter, such as excess presence of organic matter (Rietzler *et al.*, 2001).

The average values of NH_4^+, an important indicator of recent pollution, exceeded the limit in streams Ig04 and Ig07 during the dry season. Similarly, the values of NO_3^- surpassed the limit in streams Ig01, Ig05, Ig07, and Ig10 during the same seasonal period. Changes in these parameters are generally associated with the decomposition of organic matter, discharge of domestic and industrial effluents (Braga *et al.*, 2018; Mulliss *et al.*, 1996; Ren *et al.*, 2014), NO_3^-, levels may result from the use of fertilizers containing nitrogen compounds in agricultural activities (Bijay-Singh and Craswell, 2021; Figueiredo *et al.*, 2010). Streams Ig01 and Ig10, located in areas with a considerable density of rural properties, are influenced by agricultural activities. In streams Ig05 and Ig07, the high values may be explained by the discharge of domestic effluents, as these systems are more distant from agricultural areas. The presence of elevated NH_4^+ and NO_3^- levels in these streams suggests potential sources of contamination and highlights the impact of anthropogenic activities on water quality.

Similar to Ferreira *et al.* (2021), there is the potential capacity for assimilation of anthropogenic pollution by the streams when the disturbance is limited in space, time, and intensity. This demonstrates that peri-urban activities do not significantly impact water quality. Furthermore, while peri-urban activities slightly affect the natural pattern of water quality on a finer seasonal scale, these changes remain moderate compared to the original water quality pattern. These findings suggest that in peri-urban areas, streams have a capacity to deal with anthropogenic pollution to some extent, and seasonal changes in water quality are more pronounced in urban areas than in peri-urban areas.

3.4. Microbiological Analysis

Presence of total coliforms was confirmed in all streams, with fecal coliforms, specifically *E. coli*, detected in all streams except Ig03 and Ig09. These microorganisms serve as primary indicators of fecal contamination, reflecting the absence of basic sanitation and the discharge of domestic effluents into the streams (Prado *et al.*, 2023; Saxena *et al.*, 2015; Tillett *et al.*, 2018), especially those located in urban areas, classified as intermediate and degraded. Only one of the streams classified as preserved, Ig10, showed presence of *E. coli*. Despite its location in an area with low residential density, a few kilometers from the urban center, and with no evidence of domestic effluent discharge in the sampled stretch, this stream is situated near the municipal landfill and is influenced by the unhealthy conditions of its surroundings. Additionally, it is contaminated by the groundwater table.

In streams classified as intermediate and degraded, the effects of disorderly urbanization are more pronounced and have led to uncontrolled and over occupation of watercourses. This has resulted in the direct discharge of domestic effluents into the streams, intensifying the organic matter load, as evidenced by the previously discussed limnological parameters. This condition can negatively impact aquatic fauna (Qadri and Faiq, 2020). Additionally, direct contact or ingestion of contaminated water can cause gastrointestinal diseases, posing serious health risks to urban communities reliant on these water resources (Jagai *et al.*, 2019; Qadri and Faiq, 2020; Rodríguez-Tapia and Morales-Novelo, 2017).

3.5. Relationships between Variables and Point Clustering

The Redundancy Analysis (RDA) revealed that substrate types M (mud), RO (roots), and PA (plant aquatic) influence the values of BOD in degraded streams (Figure 3a). In preserved streams, OD is influenced by characteristics related to riparian forest conditions (CRF, WRF, and CC) and the absence of anthropogenic influence (AHO, ABD, and ADIE). The analysis also demonstrated that substrates F and ST influenced pH, TB, SO_4^{2-} and Cl values in intermediate streams. These results highlight the importance of different substrate types in water quality and nutrient dynamics in degraded and preserved streams. However, the statistical significance test of the analysis did not reveal a significant relationship between the dependent variables (limnological) and the independent variables (HII+hydromorphological), with a p-value of 0.48. Some factors may have limited the detection of relationships between variables in this study. These include sample units, absence of control points (in all urban areas), and the complexity of the studied aquatic systems. Additionally, there are other factors not considered in this analysis that influence limnological characteristics, as well as interactions among different components of the aquatic ecosystem.

Cluster Analysis reveals three groups (Figure 3b). The first group comprises four streams classified as degraded based on the HII - Ig04, Ig06, Ig07, and Ig08. The second group consists of intermediate streams (Ig01 and Ig02), one degraded stream (Ig05), and one preserved stream (Ig10). Finally, the third group comprises preserved streams (Ig03 and Ig09). This result underscores the importance of integrating environmental, hydro-morphological, and limnological metrics to assess ecosystem health more accurately. When considering all the analyzed parameters, Ig10 was not grouped with the preserved streams, and Ig05 was not grouped with the degraded ones. Both streams exhibit distinct characteristics that justify their classification into specific groups. Ig05, despite being located in an urban area with high residential and population density, is an environment where the local community undertakes consistent preservation and care actions for the stream and its surrounding area. These actions include avoiding the discharge of domestic effluents in the sampled stretch and preserving natural features by planting trees and conducting clean-up activities. On the other hand, Ig10, as mentioned earlier, despite having preserved riparian characteristics that classify it as "preserved" according to the Hydromorphological Integrity Index (HII), is influenced by the nearby landfill and agricultural activities in the region. These influences have negatively impacted the limnological characteristics of the stream, despite maintaining riparian vegetation integrity.

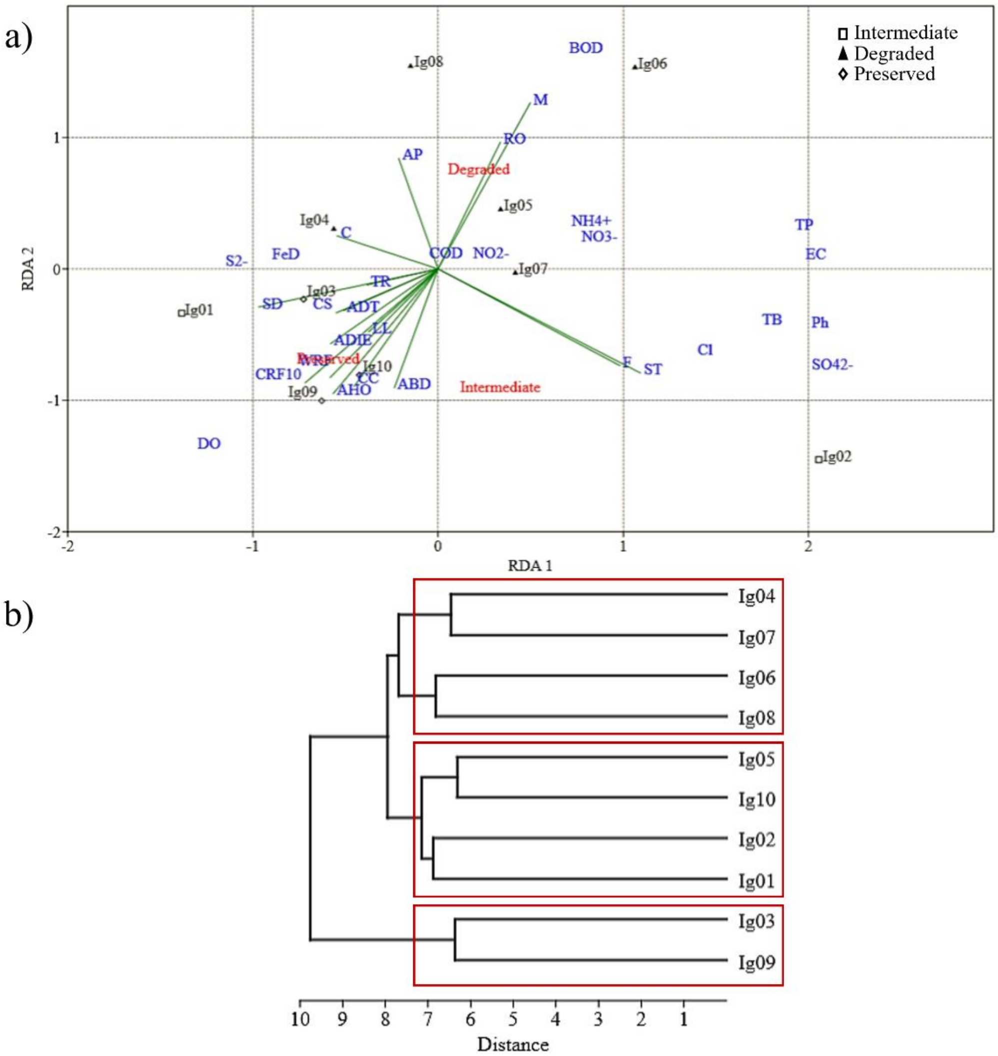

Figure 3. a) Results of Redundancy Analysis (RDA) Highlighting the Relationship Between Environmental, Hydromorphological, and Limnological Variables. b) Hierarchical Cluster Analysis.

Our results provide valuable insights into the conditions of urban streams in Southwest Amazon, presenting a representative overview of these ecosystems in urban environments. Although our study was limited to the city of Porto Velho, whose unique environmental, socioeconomic, and cultural characteristics may influence water quality patterns distinctly, similar situations may be found in other Amazonian cities with comparable features to Porto Velho. The lack of effective measures to preserve the natural characteristics of these ecosystems will have a negative impact on the ecosystem services they provide. Furthermore, alterations in the physical characteristics of the habitat and water quality in these ecosystems pose a threat to biodiversity, as aquatic communities rely on these characteristics for their structure (Cunha *et al.*, 2022; Monteiro-Junior *et al.*, 2014; Silva-Santos *et al.*, 2023). Therefore, adopting appropriate conservation actions is crucial to ensure the sustainability of these important aquatic environments in urban settings.

5. CONCLUSION

The results of this study reveal the influence of urbanization on streams in the Southwestern Amazon, with pronounced impacts on the environmental, hydromorphological, and limnological integrity of these ecosystems. The analysis of water physico-chemical parameters highlighted differences among preserved, intermediate, and degraded streams, emphasizing the interconnectedness of environmental, hydromorphological, and limnological characteristics. The presence of preserved vegetation and high vegetative cover proved crucial for maintaining water quality, while urbanization and anthropogenic activities negatively impacted stream integrity. Given that this study reveals concerning conditions regarding physical and limnological integrity in the analyzed streams, it is crucial to further investigate the effects of these poor conditions on local biodiversity, especially for aquatic species. Additionally, an integrated approach that considers not only limnological and environmental aspects, but also socioeconomic and health factors is essential to provide a holistic understanding of the health of these ecosystems and to comprehend the relationships among their various components.

The identification of threats to the health of these ecosystems underscores the importance of considering specific regional criteria for accurate assessment and targeted public policies are needed for the protection and preservation of these aquatic environments. These findings emphasize the need for mitigating measures and the implementation of conservation strategies adapted to the unique characteristics of urban streams in the region. The development of recovery and management strategies, coupled with long-term monitoring programs, emerge as fundamental tools to mitigate negative impacts and promote the sustainability of these ecosystems.

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