UNIVERSIDADE FEDERAL DE LAVRAS

ALICE ARANTES CARNEIRO

BENTHONIC MACROINVERTEBRATES IN SPRINGS IN DIFFERENT LAND USE

LAVRAS – MG
2024

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ecologia Aplicada, área de concentração em Ecologia e Conservação de Recursos em Paisagens Fragmentadas e Agrossistemas para a obtenção do título de Doutor.

Dra Alessandra Angélica de Pádua Bueno
Orientadora

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MACROINVERTEBRADOS BENTÔNICOS EM NASCENTES SOB DIFERENTES USOS DO SOLO

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RESUMO GERAL

A presente tese está organizada em três partes, a primeira apresenta uma introdução geral e os objetivos gerais, a segunda apresenta dois capítulos originais (manuscritos) a serem submetidos a revistas científicas. O primeiro manuscrito submetido a uma revista científica, intitulado ―Changes in land use affect the benthic macroinvertebrate community in springs: a systematic review‖ objetiva responder a seguinte questão: Quais os efeitos dos diferentes usos do solo na diversidade de macroinvertebrados bentônicos nas nascentes? Foi aplicado o fluxo de trabalho PRISMA. Nossos achados revelaram deterioração da qualidade da água bem como perda na biodiversidade de macroinvertebrados bentônicos em nascentes com perturbações antrópicas. No segundo manuscrito a ser submetido, intitulado "Does the gradient of environmental degradation affect the macroinvertebrate community in springs?" investigamos como as modificações no uso da terra afetam a comunidade bentônica em quarenta nascentes em áreas de mata nativa, eucalipto, pastagem e urbana. Os resultados mostraram que diferentes usos da terra afetaram a riqueza, composição e diversidade funcional da comunidade de macroinvertebrados bentônicos com maiores perdas relacionadas às nascentes em áreas urbanas. A tese apresenta ainda a terceira parte de divulgação científica que gerou como produto, o mini-book ―Conhecer para conservar: A bacia hidrográfica do Ribeirão Ipanema‖.

Palavras-chave: biodiversidade; macroinvertebrados bentônicos; mananciais.

ABSTRACT

The present thesis is organized into three parts. The first part presents a general introduction and the overall objectives. The second part includes two original chapters (manuscripts) intended for submission to scientific journals. The first manuscript, submitted to a scientific journal and titled *"Changes in land use affect the benthic macroinvertebrate community in springs: a systematic review"*, aims to answer the following question: What are the effects of different land uses on the diversity of benthic macroinvertebrates in springs? The PRISMA workflow was applied. Our findings revealed water quality deterioration as well as biodiversity loss of benthic macroinvertebrates in springs with anthropogenic disturbances. The second manuscript, titled *"Does the gradient of environmental degradation affect the macroinvertebrate community in springs?"*, investigates how land use changes affect the benthic community in forty springs located in areas of native forest, eucalyptus plantations, pasture, and urban zones. The results showed that different land uses impacted the richness, composition, and functional diversity of the benthic macroinvertebrate community, with the greatest losses associated with springs in urban areas. The third part of the thesis focuses on scientific dissemination, resulting in the production of the mini-book *"Conhecer para conservar: A bacia hidrográfica do Ribeirão Ipanema"* ("Know to conserve: The Ribeirão Ipanema watershed").

Keywords: biodiversity; benthic macroinvertebrates; water sources.

INDICADORES DE IMPACTO

O objetivo principal da tese foi identificar como as mudanças no uso da terra afetam a estrutura, diversidade e composição da fauna bentônica em nascentes. Nesse cenário nossa pesquisa representa o primeiro esforço documentado da diversidade taxonômica e funcional da comunidade de macroinvertebrados para as nascentes sob diferentes usos da terra na bacia do Ribeirão Ipanema. Nossos achados fornecem informações valiosas sobre o efeito nocivo da supressão da vegetação nativa e/ou substituição da mata ciliar, sobre a integridade ecológica de nascentes. A comunidade de macroinvertebrados bentônicos provou ser um importante bioindicador para nosso entendimento sobre os efeitos da alteração no uso da terra sobre a diversidade e riqueza da fauna bentônica em nascentes. Além disso, produzimos um mini- book de divulgação científica —Conhecer para conservar: a bacia hidrográfica do Ribeirão Ipanema‖ com o propósito de fornecer conhecimento sobre a fauna aquática como bioindicadores de qualidade de água, bem como, despertar no leitor o sentimento de pertencimento e cidadania. —Conhecer para conservar: a bacia do Ribeirão Ipanema‖ é uma obra que transcende a sala de aula e os muros da escola. A formação de cidadãos atuantes em ações de conservação e recuperação ambiental são efetivas por meio de conhecimentos e consciência técnico-científica para formação de uma sociedade sustentável. Embasada na BNCC, a Base Nacional Comum Curricular e nos ODS – Objetivos para o desenvolvimento sustentável, a obra apresenta conceitos sobre bacia hidrográfica, unidades de conservação, ciclo da água, mudanças de estado físico da água, influência do uso, ocupação e degradação do solo na qualidade da água e organismos bioindicadores ambientais. Os impactos sociais, tecnológicos, econômicos, e/ou cultural estabeleceram caráter extensionistas com participação e atuação na sociedade externa à UFLA com a parceria do Instituto Interagir em atividades nas escolas públicas e privadas do Vale do Aço. Desde 2022 e até o presente momento o projeto intitulado —Nascentes do Ipanema‖ desenvolveu, e desenvolve, diversas ações como palestras, oficinas e plantio de mudas para recuperação de nascentes da bacia hidrográfica do Ribeirão Ipanema. Algumas atividades mencionadas tiveram repercussão na mídia local, e se encontram descritas na terceira parte desta tese. Os indicadores de impacto se enquadram dentro das áreas temáticas da Política Nacional de extensão, que correspondem aos grandes focos de política social nas quais podemos destacar: 1 - comunicação, 4 - educação, 5 - meio ambiente. Os impactos da presente tese estão alinhados ainda aos 17 Objetivos de

Desenvolvimento Sustentável (ODS) da Organização das Nações Unidas (ONU) para que o Brasil cumpra a Agenda 2030 sendo eles: 4 – Educação de qualidade e 14 – Vida na água.

IMPACT INDICATOR

The main objective of the thesis was to identify how land-use changes affect the structure, diversity, and composition of benthic fauna in springs. In this context, our research represents the first documented effort to assess the taxonomic and functional diversity of macroinvertebrate communities in springs under different land uses in the Ribeirão Ipanema basin. Our findings provide valuable insights into the harmful effects of native vegetation suppression and/or replacement of riparian forests on the ecological integrity of springs. The benthic macroinvertebrate community proved to be a valuable bioindicator for our understanding of the effects of land-use changes on the diversity and richness of benthic fauna in springs. Furthermore, we produced a scientific outreach book, ―Conhecer para conservar: a bacia hidrográfica do Ribeirão Ipanema‖ (To Know is to Conserve: The Ribeirão Ipanema Watershed), with the aim of providing knowledge about aquatic fauna as bioindicator organisms of water quality, as well as instilling a sense of belonging and citizenship in the reader. ―Conhecer para conservar: a bacia do Ribeirão Ipanema‖ is a work that transcends the classroom and the school walls. The formation of active citizens in conservation and environmental recovery actions is effective through technical-scientific knowledge and awareness, contributing to the formation of a sustainable society. Based on the BNCC (Base Nacional Comum Curricular), the work presents concepts on watershed, conservation units, water cycle, physical state changes of water, and the influence of land use, occupation, and degradation on water quality and environmental bioindicator organisms. The social, technological, economic, and/or cultural impacts established an extensionist character with participation and involvement in society outside UFLA, in partnership with the Instituto Interagir, in activities at public and private schools in the Vale do Aço. In 2023 and up to the present moment, the project entitled ―Nascentes do Ipanema‖ (Ipanema Springs) has developed various activities such as lectures, workshops, and tree planting for the recovery of springs in the Ribeirão Ipanema watershed. Some of the activities mentioned had repercussions in the local media and are described in the third part of this thesis. The impact indicators align with the thematic areas of the National Extension Policy, which correspond to the major focuses of social policy, including: 1 - communication, 4 - education, 5 - environment. The impacts are also aligned with the 17 Sustainable Development Goals

(SDGs) of the United Nations (UN) for Brazil to meet the 2030 Agenda, namely: 4 – Quality Education and 14 – Life Below Water.

SUMÁRIO

PRIMEIRA PARTE

INTRODUÇÃO GERAL

Compreender como os impactos antrópicos afetam a biodiversidade é um dos grandes desafios da ecologia. Ambientes aquáticos vêm cada vez mais recebendo atenção dos ecólogos, dada à relevância ambiental, social e econômica desse recurso. As nascentes, especialmente, são ambientes aquáticos com características únicas que fornecem serviços ecossitêmicos fundamentais tornando-se ambientes relevantes para a conservação (Dumnicka et al., 2013; Peixoto et al., 2024; Staudacher and Fureder, 2007).

Nascentes apresentam como característica marcante águas subterrâneas que emergem para a superfície e criam ecótonos aquáticos-terrestres e subterrâneos-superficiais consistindo em uma relevante contribuição para a diversidade regional de ecossistemas ducícolas (Ilmonen et al., 2009), sendo, portanto, consideradas, hots pots para biodiversidade aquática (Ako et al al., 2012; Fashina et al., 2023; Lehosmaa et al., 2017). Processos ecológicos fundamentais em ecossistemas aquáticos como ciclagem de nutrientes e fluxo de energia são influenciados por insetos aquáticos, (Bhat et al., 2022; Von Fumetti and Blattner, 2017) organismos que desempenham papel crucial na dinâmica desses ambientes e podem ser estudados como bioindicadores eficazes da qualidade da água (Bueno et al., 2003; Costa et al., 2024; Peixoto et al., 2015).

Nascentes são áreas protegidas por lei e devem apresentar APP – Área de Proteção Permanente de 50 metros de raio (Brasil, 2012), ainda assim, são frequentemente ameaçadas pelas alterações no uso da terra que ocorrem na bacia de drenagem podendo afetar suas características naturais, diversidade de espécies e a qualidade de suas águas (Marmontel and Rodrigues, 2015; Stevens et al, 2021). Essas alterações, especialmente a remoção e/ou substituição da cobertura vegetal original por pastagem, urbanização e atividades agrossilvopastoris, geram impactos negativos e criam gradientes ambientais que podem alterar a estrutura e composição da fauna aquática (Fekadu et al., 2022; Peixoto et al., 2024). Vários estudos (Allan, 2004; Nessimian et al., 2008; Da Silva et al., 2015; Peixoto et al., 2024) evidenciaram os efeitos dos diferentes tipos de cobertura vegetal sobre o ambiente aquático, revelando deterioração da qualidade ecológica de corpos d’água com perda da heterogeneidade ambiental, em decorrência da supressão de vegetação ripária. As áreas de entorno dos ecossistemas aquáticos, tem papel fundamental pois funcionam como zonas de amortecimento, reduzem a entrada de material alóctone, auxiliam na estabilização das margens, garantem a conservação da biodiversidade e o fornecimento de serviços ecossistêmicos essenciais, como água de boa qualidade para consumo da população (Zhang et al., 2019).

A fauna de invertebrados aquáticos é frequentemente utilizada como bioindicadores (Bastos-Pereira and Bueno, 2016; Bonada et al., 2006) pois são organismos cosmopolitas, apresentam elevada riqueza de táxons com graus diferentes de sensibilidade às alterações antrópicas na bacia de drenagem, tem o ciclo de vida relativamente longo e são sésseis permitindo estudos em escala temporal e espacial (Callisto et al., 2001). As áreas de entorno de nascentes desempenham, portanto, papel relevante nas características físicas e químicas da água, bem como do sedimento e estas por sua vez afetam a composição e estrutura da comunidade bentônica (Jun et al., 2011; Nessimian et al., 2008; Parreira de Castro et al., 2016). Assim, devido às alterações no uso da terra, frequentemente intensificado, a biota aquática de nascentes tornou-se fortemente ameaçada em muitas regiões do planeta (Kim et al., 2016).

As nascentes tornam-se habitats ideais para estudar as relações entre as comunidades faunísticas e os parâmetros ambientais que influenciam sua estrutura, possibilitando investigar sobre os mecanismos responsáveis pelo estabelecimento e manutenção da biodiversidade (Peixoto et al., 2024). O conhecimento dos fatores que influenciam a variação da comunidade de macroinvertebrados bentônicos é necessário para identificar mudanças na biodiversidade devido a causas naturais e antropogênicas (Callisto et al., 2019; Collier and Quinn, 2003; Jonsson et al., 2017). Além disso, torna-se necessária uma investigação acerca de como a intensidade da perturbação pode alterar a dinâmica das comunidades biológicas de nascentes. Com a crescente e acelerada perda dos ecossistemas naturais e consequente perda de espécies, torna-se necessário conhecer a riqueza e diversidade de invertebrados aquáticos em nascentes já que estas, muitas vezes, algumas espécies, são ainda desconhecidas pela ciência. Além disso é importante conhecer como a riqueza e a diversidade de macroinvertebrados bentônicos respondem distintos impactos em nascentes sob diferentes usos do solo.

Considerando os aspectos acima mencionados, a presente tese é o primeiro registro de invertebrados aquáticos em nascentes na sub-bacia do Ribeirão Ipanema, apresenta dois capítulos originais organizados como manuscritos a serem submetidos a revistas científicas, além da divulgação científica que gerou como produto um mini-book ―Conhecer para conservar: A bacia hidrográfica do Ribeirão Ipanema‖. O primeiro capítulo trata de uma revisão sistemática com o intuito de avaliar o estado atual do conhecimento sobre como os diferentes usos da terra afetam a diversidade de macroinvertebrados bentônicos nas nascentes.

O segundo capítulo explora o efeito das alterações do uso da terra na estrutura, composição e diversidade da comunidade bentônica em nascentes, na sub-bacia do Ribeirão Ipanema, leste de Minas Gerais. O nosso objetivo geral é, portanto, entender como a mudança no uso da terra, devido às atividades antrópicas, altera a estrutura da fauna bentônica em nascentes. Além desses capítulos, a tese inclui esta introdução geral e conclusão geral.

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SEGUNDA PARTE

ARTIGOS

ARTIGO 1

Changes in land use affect the benthic macroinvertebrate community in springs: a systematic review

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Changes in land use affect the benthic macroinvertebrate community in springs: a systematic review

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Abstract

Studies on the impacts of land use on the benthic community in springs are relevant and urgent given the accelerated degradation of surface aquatic ecosystems they have been subjected to. Our objective was to assess the current state of knowledge on how different land uses affect the diversity of benthic macroinvertebrates in springs. The main question we sought to answer in this systematic review was: ―What are the effects of different land uses on the diversity of benthic macroinvertebrates in springs?‖ The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used to guide the driving of this review. Articles that did not meet the defined criteria were removed, and 11 studies were selected. We added 1 more study selected through the reference list, totaling 12 studies analyzed. Our results showed that the response pattern of macroinvertebrates to the gradient of environmental degradation presents tolerant taxa increasing in impacted conditions. Temperature and electrical conductivity were evaluated in 11 studies, demonstrating that they are the main important physicochemical parameters of water quality analyzed in studies on benthic communities in springs, along with dissolved oxygen, which was evaluated in 9 studies. Most studies (ten) demonstrated that the richness and diversity of benthic macroinvertebrates increased with the degree of preservation in springs. The replacement of natural vegetation areas with agricultural and forestry areas causes the homogenization and reduction of riparian vegetation, harming natural ecological mechanisms and affecting the benthic macroinvertebrate fauna. Our findings warn about the risk of environmental degradation caused by changes in land use, leading to biodiversity loss in springs, which are crucial for the survival of all biota. Furthermore, the benthic macroinvertebrate community has proven to be a valuable bioindicator for our understanding of the effects of land use changes on the diversity and richness of benthic fauna in springs.

Keywords: benthos; springs; PRISMA; and land use.

1 Introduction

Natural aquatic ecosystems have been increasingly remodeled to meet the growing demands of the human population. These changes alter land use for agricultural, industrial, and urban purposes, consequently leading to modifications in the quality of surface waters (Ilmonen et al., 2012; Reiss and Chifflard, 2018; Rozkowski and Dumnicka, 2010). Balancing social and ecological needs in water use is a challenge.

Even though legally protected, springs are often threatened by alterations occurring in the watershed, which can affect their natural characteristics, species diversity, and water quality (Keleher and Rader, 2008; Marmontel et al., 2018; Stevens et al., 2021). Changes in land use can also generate negative environmental impacts that affect the structure and composition of aquatic fauna (Johnson et al., 1993; Luczkovich et al., 2002; Sitati et al., 2021). Studies conducted in streams (Allan, 2004; Amaral et al., 2015; Bonada et al., 2006; Hepp et al., 2010; Nessimian et al., 2008) have shown the effects of different types of vegetation cover on benthic fauna. These studies reveal the deterioration of ecological quality in water bodies due to riparian vegetation suppression, leading to loss of environmental heterogeneity and consequently, diversity. However, studies that evaluate the effects of different land uses on the aquatic macroinvertebrate community in springs are still scarce.

Springs are important environments for maintaining biodiversity and provide crucial ecosystem services such as water for human consumption, making them relevant for conservation studies (Biggs et al., 2017; Kabir et al., 2024; Stevens et al., 2021). The distribution and occurrence of aquatic invertebrates are influenced by regional and local biogeographic patterns, depending on predominant environmental characteristics such as water speed, substrate type, food availability, predator shelter, and environmental homeostasis (Merritt et al., 2017). Benthic macroinvertebrates are essential elements in the structure and functioning of water bodies, playing a crucial role in nutrient dynamics and cycling, also serving as environmental bioindicators (Burch et al., 2022; Cibik et al., 2022). Thus, studies on the impacts of land use on benthic communities are relevant and urgent given the accelerated degradation of surface aquatic ecosystems they have been subjected to.

Our objective was to assess the current state of knowledge on how different land uses affect the diversity of benthic macroinvertebrates in springs. Here, we conducted a systematic review to address: (i) Which taxonomic groups and types of land use were studied? (ii) What are the main variables influencing the diversity of benthic macroinvertebrates? The main question we sought to answer in this systematic review was: "What are the effects of different land uses on the diversity of benthic macroinvertebrates in springs?".

2 Methods

2.1 Guiding question, databases, and PRISMA workflow

The main question we aimed to address in this systematic review was: "What are the effects of different land uses on the diversity of benthic macroinvertebrates in springs?". The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were employed to guide the preparation of this review (Moher et al., 2015; Page et al., 2021). The PRISMA workflow was applied considering two complementary search strategies to retrieve potentially relevant studies: (i) primary search in two comprehensive electronic databases (Scopus and Web of Sciences), and (ii) secondary search through manual screening of the reference lists of all relevant studies retrieved in the primary search.

2.2 Search filters and search strategy

On March 24, 2023, we conducted a bibliographic search in the expanded ISI Science Citation Index database using the following combination of relevant keywords: ("*springs*" OR "*headwater*") AND ("*Invertebrates*" OR "*Macroinvertebrates*" OR "*Aquatic community*" OR "*Aquatic fauna*" OR "*Aquatic insects*" OR "*Aquatic assemblages*" OR "*Aquatic species*" OR "*Benthic community*" OR "*Benthic fauna*" OR "*Benthic assemblages*" OR "*Benthic species*") AND ("*Land use*" OR "*Land cover*" OR "*Land management*"). To broaden the scope of our search strategy, the reference lists of each relevant study identified across all databases were manually screened to identify additional potentially relevant studies. All relevant studies published up to March 2023, indexed and retrieved in full text, were included in the systematic review. No chronological or language limits were applied in our search strategy. The complete search strategy and results are described in the supplementary files.

2.3 Screening of records, retrieval of relevant studies, and exclusion criteria

Only studies investigating benthic fauna in springs under different land uses were included in this systematic review. This selection was based on the PRISMA workflow (Moher et al., 2015), conducted independently by reviewers (R.P.R.C and A.A.P.B). Initially, all research records retrieved from electronic databases were imported into the Mendeley Reference Management Program (Mendeley, London, Westminster, United Kingdom), which was used to remove duplicates by comparing indexing metadata (e.g., titles, authors, year, volume, issue, journal, and DOI) from all databases. Subsequently, the title and abstract of all research records were screened, excluding those not related to the research topic. Next, all potentially relevant records were retrieved in full text and assessed for eligibility according to specific inclusion and exclusion criteria. Potential discrepancies at any of these stages were resolved by arbitration (R.R.C) by an expert researcher (A.A.P.B). All exclusion criteria were equally applied in both primary and secondary search strategies. The complete PRISMA workflow obtained from our search strategy is presented in figure 1.

2.4 Exclusion criteria

Studies were deemed irrelevant and excluded if they: (i) did not report the effect of different land uses on benthic macroinvertebrates in springs, (ii) were non-original investigations (e.g., literature reviews, editorials, letters, congress abstracts), (iii) investigated other biological groups such as birds, mammals, or terrestrial insects, (iv) studied low-order streams (1st to 3rd order). All exclusion criteria were equally applied in both primary and secondary search strategies.

3 Results and Discussion

3.1 Included Studies

The initial search yielded 880 articles from Scopus and Web of Science databases. After removing 246 duplicate articles, 634 articles were screened by title and abstract. Articles that did not meet the defined criteria were also excluded, resulting in 11 studies being selected. An additional 1 study was added through the reference list of the initial eleven included articles. Therefore, a total of twelve studies were considered for this systematic review. The flowchart that summarizes the literature search process is presented in figure 1. References for all included studies are provided in the supplementary material.

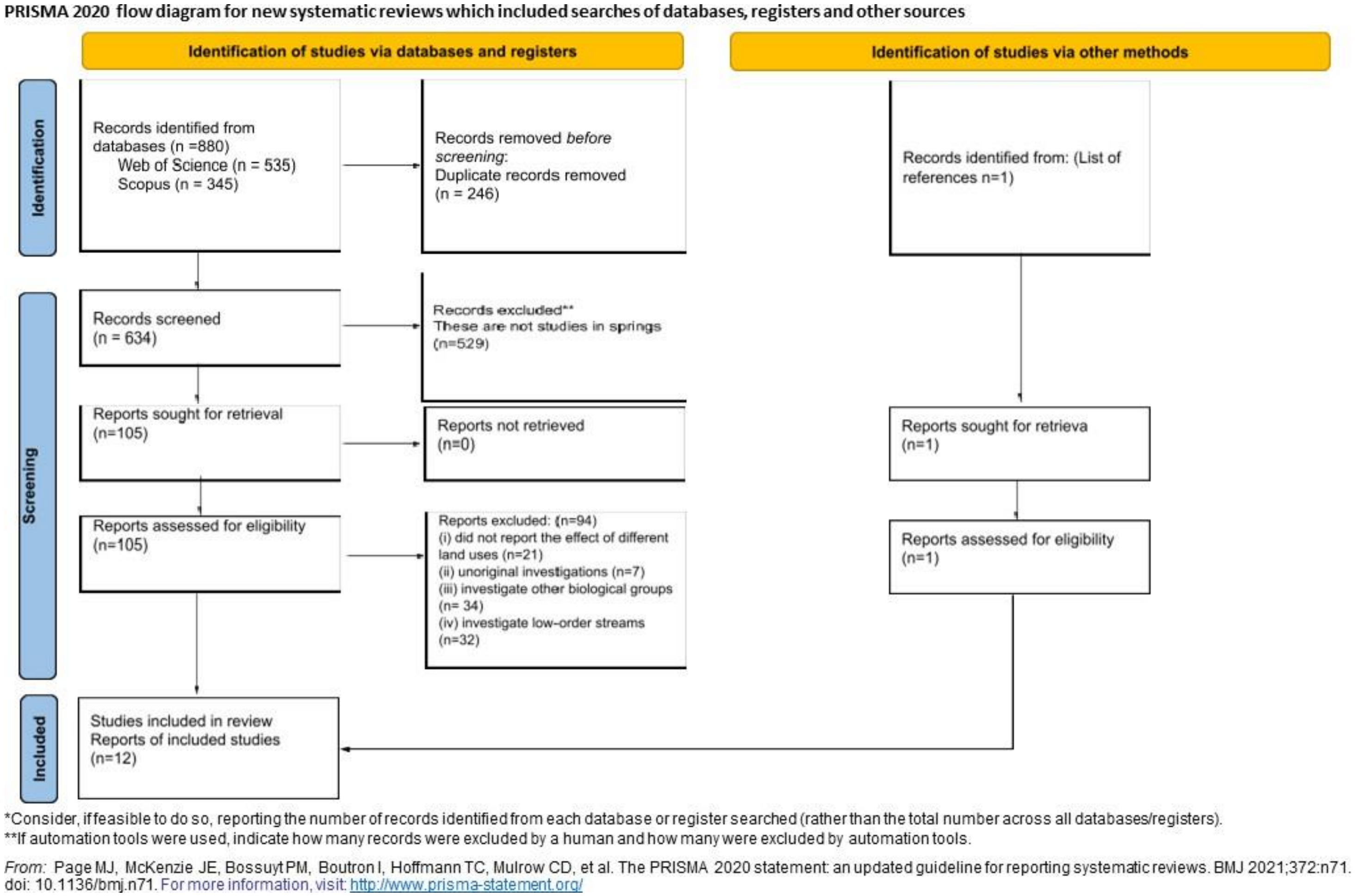
The studies selected for this systematic review were conducted primarily in the USA, Poland, Finland (2 each), Brazil, Canada, France, Italy, and Switzerland (1 each). One review study assessed the current and historical evolution of water resources. The search results showed that surface water and groundwater are interconnected, and total water storage varied across regions over the century. Some regions, such as the US Central Valley, experienced declines in water storage. This same study demonstrated that water resources can be affected by human intervention directly through water use, particularly irrigation, and indirectly through land use changes, such as agricultural expansion and urbanization (Scanlon et al., 2023).

In addition to the above facts, springs have become a focus of biodiversity studies (Reiss et al., 2016; Reiss and Chifflard, 2018; Sada et al., 2005), especially in countries with water scarcity or high rates of water resource utilization, such as Poland and Finland, which could face water shortages due to climate change. These countries, despite not currently experiencing water stress, may face drought and scarcity situations primarily due to climate changes.

Ensuring water availability faces challenges arising from anthropogenic activities, as well as climate change, with the USA, along with China and India, being the countries with the highest water consumption worldwide and at risk of water scarcity. (Metha et al., 2024; Ritchie and Roser, 2023).

3.2 Number of Studied Springs, Taxonomic Groups, and Land Use Types

The number of springs assessed in the studies varies, as demonstrated in Table 1. This ranged from five to 125 springs. Some studies examined a limited number, between five or 13 springs, while others utilized a broader set, reaching up to 125 studied springs. However, most studies (75%) evaluated between 16 to 86 springs. The diversity in these numbers reflects the lack of consensus in the literature on the ideal sample size, influenced by the study's purpose, ecosystem complexity, and available research funding. However, studies assessing a larger number of springs under varied environmental conditions tend to produce more robust results and may lead to more reliable conclusions (Rumschlag, et al., 2023; Simaika et al., 2024).



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Figure 1 – Flow diagram of search results to define the articles to be included in systematic review.

All studies analyzed benthic fauna in areas with different degrees of disturbance, comparing reference areas with those under some degree of negative impact. Natural ecosystems are increasingly rare worldwide. Continuous areas of preserved vegetation are significantly reducing due to a series of human activities such as mining, urbanization, agriculture, pasture, and planting of timber species (Caldero et al., 2023; Khan et al., 2023). The loss of natural areas has been a global concern for biodiversity conservation, as it is one of the leading causes of mass extinction; furthermore, aquatic ecosystems have become one of the most threatened ecosystems in the world (Bacani et al., 2015; Liu et al., 2023; Xiong et al., 2023). In this context, three studies compared preserved areas with disturbed areas, classified as mild, moderate, and severe disturbances. The remaining studies compared natural areas with anthropogenic areas, including managed forests, eucalyptus forests, agricultural areas, built and exploited areas, and pastures (Table 1).

Land use and vegetation cover measures are indicators of different environmental degradation gradients in the landscape, widely used to monitor stream conditions, particularly through benthic macroinvertebrates as bioindicators (Deborde et al., 2016; Dos Santos et al., 2024). Negative environmental impacts on water quality have been reported by several authors, especially those resulting from the replacement of natural vegetation by urban areas (Huang and Gergel, 2023; Mahmud et al., 2024; Zemo et al., 2023), pastures and agriculture (Trau et al., 2024), and eucalyptus monocultures (Werku and Bulto, 2023).

Recent studies have indicated that the benthic macroinvertebrate community responds differently to the environmental degradation gradient caused by various anthropogenic activities (Lee et al., 2020; Liu et al., 2021; Paz et al., 2023; Scotti et al., 2020). The pattern of response of macroinvertebrates to the environmental degradation gradient based on taxonomy is well established in the literature (Liu et al., 2021; Marrochi et al., 2021; Taborda et al., 2022), with tolerant taxa increasing under impacted conditions while sensitive taxa increase with decreasing degradation (Huang and Gergel; 2023; Werku and Bulto; 2023). In this context, most studies included in this review evaluated the total fauna of benthic macroinvertebrates collected during the studies, where all collected individuals were sorted, identified, and included in the data. In these studies, the taxonomic groups analyzed predominately included the family Chironomidae (83.3%). Among Diptera families, Chironomidae is the richest in species and number of individuals in aquatic environments, is cosmopolitan, and has a wide geographical distribution (Serra et al., 2017). They are capable of tolerating a wide range of environmental conditions and show a certain degree of tolerance to environmental disturbances due to the presence of hemoglobin in several species, such as Chironomus plumosus and Chironomus riparius, which can tolerate low concentrations of dissolved oxygen in water and are often used as bioindicators of poor water quality environments (Doric et al., 2024; Lencioni et al., 2011; Serra et al., 2017). It is important to mention that in this review, one study was included that exclusively evaluated the Chironomidae fauna, highlighting the relevance of these macroinvertebrates in the study.

Table 1 - Reference, location, number of studied springs, land use type, taxonomic groups, main taxa, and number of taxa in studies of benthic macroinvertebrates in springs under different land uses.

Reference	**Localization**	**Number of springs**	**Land use**	**Biological group**	**Main biological groups**	**Number of taxa**
(Sada et al. 2005)	USA	45	Spring Mountains disturbances vs Spring Mountains nature (spring undisturbed, slightly disturbed, moderately disturbed, or highly disturbed)	Total fauna	Species richness of the total fauna of benthic macroinvertebrates. All taxa are native to the Spring Mountains.	48
(Reiss and Chifflard, 2018)	Germany	86	Deciduous forest vs coniferous forest	Total fauna	Greater richness in more stable locations (preserved area) Deciduous Forest (*Bythinella dunker* and *Gammarus fossarum*) Coniferous forest (*Bythinella dunkeri* and *Anacena sp.*).	52
(Von Fumeti and Nagel, 2012)	Switzerland	5	Preserved forest vs Managed forest	Total fauna	Preserved Forest and Managed Forest (*Chironomidae* and *Polycelis felina*).	56
(Lencioni et al. 2011)	Italy	81	Siliceous vs carbonate basins (altitude gradient)	Chironomidae	Species of the genera *Diamesa* and *Eukiefferiella*, such as *Diamesa cinerella* and *Diamesa tonsa*, *Diamesa incallida and Eukiefferiella tirolensis*, *Diamesa insignipes*, *Diamesa latitarsis*, *Diamesa starmachi*, *Eukiefferiella cyanea*, *Eukiefferiella devonica gr.*, *Eukiefferiella similis.*	98
(Amaral et al. 2021)	Brazil	20	Nativa forest vs Eucalyptus	EPT	Ephemeroptera, Plecoptera and Trichoptera (EPT).	17
(Leshosmaa et al. 2018)	Finland	20	Preserved area, agricultural area, built areas, explored areas	Total fauna	Chironomidae (46,5%), other diptera (19%), coleoptera (10%) and trichoptera (10%).	147
(Okon et al. 2020)	Poland	13	Forest springs X	Total fauna	*Crenobia alpina* (planariidae).	

			anthropogenic springs			
(Rozkowski and Dumnicka, 2010)	Poland	28	Preserved area X agricultural area	Total fauna	*Crenobia alpina* (preserved areas) and *Gianius aquedulcis* (impacted areas).	
(Claret and Marmonier, 2019)	France	16	Forest x pasture	Total Fauna	Diptera, Plecoptera and Trichoptera	46
(Ilmonen et al. 2012)	Finland	75	Preserved X Anthropic (predominance of forestry and pasture)	Total fauna	*Nemurella pictetii* (Plecoptera - Nemoridae) e *Asellus aquaticus* (Asellidae) (preservado)- *Psectrocladius limbatellus* (Chironomidae) e *Micropsectra junci* (Chironomidae).	146
(Knysh et al. 2016)	Canada	20	Forestry X Agricultural	Total fauna	Chironomidae (*Thienemanniella*, *Parochlus* and *naked Hydrobae*) for forest areas. Chironomidae (*Tanytarsini* and *Metriocnemus*), ostracods, the plecopteran genera *Sweltsa* and *Nemoura*, and *Pisidium* molluscs dominated agricultural springs.	
(Keleher and Rader, 2008)	USA	125	Forestry X moderately impacted X severely impacted	Total fauna	*Gammarus lacustris* and *Hyalella aztec*a predominated in preserved areas. Two genera of Chironomidae (*Micropsectra* + *Cricotopus*) declined with increasing disturbance. *Amphipod* abundance decreased with increasing disturbance in all classes.	302

On the other hand, one of the studies evaluated only the Ephemeroptera, Plecoptera, and Trichoptera (EPT) fauna. The orders of insects Ephemeroptera, Plecoptera, and Trichoptera (EPT) are among the aquatic organisms highlighted in limnological studies, as they are considered sensitive organisms to pollution and can indicate different degrees of degradation in aquatic environments (Akamagwuna et al., 2022; Akamagwuna et al., 2021; Guellaf et al., 2021; Serra et al., 2017). Additionally, they are shredders, collectors, and filterers of organic particles, playing a fundamental role in nutrient cycling in aquatic environments as well as in the structure of food webs (Da Silva Araújo et al., 2023; Tubic et al., 2024). A study conducted in the Republic of Serbia that analyzed EPT data in 44 streams showed that in terms of richness and number of individuals, insects were dominant in the benthic community, and of the identified insects, nearly half (63 identified taxa) belonged to the target group organisms (EPT). The study also showed that the EPT fauna in the analyzed aquatic ecosystems was altered as a result of various environmental pressures, such as organic and chemical pollution, land use and hydromorphological changes (Tubic et al., 2024).

A study by Matomela et al. (2021) collected sediment samples in nine headwater streams in natural and agriculture-disturbed environments. The data showed that compared to the preserved aquatic environments studied, the stream disturbed by agriculture presented few taxa, and in addition, there was a high abundance of tolerant taxa such as *Dicentroptelum*. The study also identified that agricultural land use is generally associated with altered water quality and habitat loss, which has been shown to be associated with corresponding changes in community composition, such as low taxonomic richness and dominance of tolerant taxa.

3.3 Environmental Variables Analyzed and Their Relationships with Fauna

Temperature and electrical conductivity were evaluated in 11 studies (91.6%) (Table 2). Water temperature is a key environmental factor that alters the structure and functioning of aquatic ecosystems (Yang et al., 2023) and can affect biological communities, especially related to global warming (Fahy et al., 2024; Sundermann et al., 2022). Moreover, water temperature can directly affect the metabolism of benthic macroinvertebrates, influencing growth and reproduction rates. Significant changes in this variable can also alter the distribution and abundance of these organisms in aquatic ecosystems (Bonacina et al., 2023; Fahy et al., 2024).

Electrical conductivity is directly linked to the presence of ionic compounds in water, originating from natural or anthropogenic processes. Natural sources of organic matter may be linked to leaching, erosion processes, or even litter deposits from surrounding vegetation in aquatic environments. Anthropogenic sources may be related to the presence of urban and industrial sewage (Paz et al., 2021), fertilizers used in agriculture, or other activities such as extensive livestock farming, all contributing organic matter inputs to aquatic systems (Lukhabi et al., 2024). Electrical conductivity alters nutrient availability, affecting the diversity of benthic macroinvertebrates (Reiss and Chifflard, 2018). A study by Rezende et al. (2014) evaluated the influence of environmental variables in streams of the Pandeiros River basin and found that electrical conductivity was the environmental variable that most influenced benthic fauna, showing that high values of electrical conductivity and non-forest areas had negative impacts on macroinvertebrate density due to habitat loss. Monitoring these variables allows detecting environmental changes that can negatively impact benthic fauna.

Nine studies (75%) analyzed the relationship between dissolved oxygen and benthic fauna (Table 2). In aquatic environments, dissolved oxygen plays a crucial role in the presence, composition, and distribution of benthic fauna, as it is essential for vital respiratory and metabolic processes for most aquatic macroinvertebrates. Protected environments often present stable and adequate dissolved oxygen concentrations to support benthic fauna (Ogbeibu and Oribhabor, 2002), while disturbed and/or degraded environments often exhibit low levels of dissolved oxygen (Sabha et al., 2022). This oxygen loss is commonly due to organic matter decomposition from domestic (Souto et al., 2011) and/or industrial sewage, as well as changes in riparian vegetation that modify land use by replacing natural areas with pastures, monocultures, and urban areas.

Benthic fauna exhibit different degrees of tolerance, with some species being resistant, tolerant, or sensitive to low dissolved oxygen, often possessing gills or other subaquatic respiratory systems (Croijmans et al., 2021). These organisms may disappear from environments where organic matter concentration is high and aerobic decomposition rates are elevated, leading to dissolved oxygen depletion (Foley et al., 2005), causing sensitive organisms to be absent from these environments.

Croijmans et al. (2021) conducted a systematic review demonstrating a relationship between temperature and dissolved oxygen rates, both influencing the composition and structure of benthic fauna, with dissolved oxygen being a better predictor of macroinvertebrate richness. The study also showed that species richness exhibited a similar pattern for both temperature and dissolved oxygen, where richness increases as dissolved oxygen levels increase.

3.4 Main Ecological Responses of the Community and Their Relationship with Land Use

Most studies, ten out of twelve (83.33%) demonstrated that species richness and diversity increased with a higher degree of preservation. Two articles showed that springs with intermediate disturbances exhibited higher richness.

Human activities degrade aquatic habitats worldwide, leading to biodiversity loss and alterations, often resulting in changes to ecosystem functions and services. Agricultural (Bacca et al., 2023; Musseau et al., 2022) and forestry (De Moura Guimarães-Souto et al., 2021; Liu et al., 2021) land uses are predominant causes of global biodiversity deterioration in aquatic environments. The replacement of natural vegetation areas by agricultural and forestry areas leads to homogenization and reduction of marginal vegetation, impairs natural sediment retention mechanisms facilitating erosion, increases organic matter input into the ecosystem, and affects the benthic macroinvertebrate fauna (Amaral et al., 2021). This study showed that the faunal composition and taxonomic richness of EPT were affected by eucalyptus plantations. Springs with greater vegetation cover (native) presented higher taxonomic richness and diversity of benthic macroinvertebrates.

A similar study by Knysh et al. (2016) (Table 2) evaluated twenty springs in eastern Canada and demonstrated that agricultural activities increased nutrient production, sediment additions, and habitat structure, which in turn altered the structure of the invertebrate community. The study also showed that forested areas were dominated by chironomids (*Thienemanniella, Parochlus*, and *Hydrobaenus*) and hydrachnid mite taxa (e.g., *Sperchon* and *Panisopsis*), while different characteristic chironomid taxa (e.g., *Tanytarsini* and *Metriocnemus*), ostracods, the plecopteran genera *Sweltsa* and *Nemoura*, and mollusks Pisidium dominated agricultural springs. *Thienemanniella* was the taxon that contributed most to the dissimilarity between springs in the two land use categories.

Urban areas are equally relevant to the degradation of environmental quality in aquatic ecosystems. A study conducted by Medupin (2020) in an urban river in the United Kingdom (UK) showed that environmental variables such as increased electrical conductivity, organic matter input, and nutrients from the urban area affected the benthic fauna, causing a reduction in biodiversity in areas with a higher percentage of urbanization. In this study, sampling points upstream of the urban area, with a lower percentage of urban cover, had organisms that can be found in clean rivers, including some organisms of the orders Ephemeroptera, Plecoptera, and Trichoptera, while Plecoptera was absent in downstream stations, further from the spring and under greater influence of the urban area.

Two articles addressed the intermediate disturbance hypothesis (Table 2). The intermediate disturbance hypothesis considers that a disturbance in a benthic community consists of two components: the disturbance and the response (Death, 2010), and it predicts that biodiversity reaches its peak at intermediate disturbance. A study conducted in a boreal watershed in China hypothesized that intermediate disturbance explains the pattern of eutrophication and biodiversity in the biological community. Results obtained in periphyton, macroinvertebrate, and fish assemblages showed that species richness was higher at intermediate levels of eutrophication, and the pattern was not impacted by other factors (Tian and Yin, 2022).

Similar results were recorded by Sada et al. (2005) and Lencioni et al. (2011) (Table 2). The first study evaluated springs in a mountain valley in Las Vegas, USA, and the second evaluated springs in siliceous and carbonate areas in Italy. Both studies showed that richness in springs with intermediate levels of disturbance was higher and that intermediate altitudes favored the diversity of benthic macroinvertebrates in springs.

Studies evaluating the water quality of springs may present limitations related to the location of collection points, as these environments may be in remote areas with difficult access. Seasonal evaluation is also a relevant factor since the benthic community responds differently to changes in water flow and climate changes. Another relevant factor that can limit studies on benthic fauna in springs is the response time of benthic macroinvertebrates, making long- term monitoring programs crucial to obtain more robust results (Leshosmaa et al. 2018).

Table 2 - Reference, location, type of land use, indices and variables, and ecological responses in studies of benthic macroinvertebrates in springs under different land uses.

Reference	Localization	Land use	Variables and indices	relationship between land use and diversity: ecological responses
(Sada et al. 2005)	USA	Spring Mountains disturbances vs Spring Mountains nature (spring undisturbed, slightly disturbed, moderately disturbed, or highly disturbed).	Temperature, conductivity, discharge, elevation.	Uniformity did not vary in relation to the disturbance. Greater richness in preserved springs or intermediate levels of disturbance. Neither elevation, water temperature, nor electrical conductance had a significant effect on species richness. The richness of aquatic macroinvertebrates in springs may be greater at intermediate levels of disturbance.
(Reiss and Chifflard, 2018)	Germany	Deciduous forest vs coniferous forest.	Temperature, electrical conductivity, pH, oxygen concentration, oxygen saturation, substrate type, Margalef richness, Shannon index, Pielou uniformity.	Greater biodiversity in species richness and total number of individuals, as well as abundances in headwaters of deciduous forests. Acidification in coniferous forest sources. Higher coverage rates of microhabitats based on organic substrate in springs of deciduous forests.
(Von Fumetia and Nagel, 2012)	Switzerland	Preserved forest vs Managed forest.	Temperature, electrical conductivity, pH, oxygen concentration, oxygen saturation, species richness, abundance, Shannon diversity, Pielou uniformity, Margalef index.	The greatest diversity (number of taxa) and greatest variability of macroinvertebrate assemblages were found in the springs with the highest maximum flow (more stable, thus the springs with the highest maximum flow differed significantly in taxonomic composition from the springs with low maximum flow. Lower taxonomic richness is often found in disturbed places, that is, places with greater flow variability.
(Lencioni et al. 2011)	Italy	Siliceous vs Carbonate basins (altitude gradient).	Conductivity, alkalinity. Hardnes, dissolved oxygen, %	Taxonomic richness and diversity peaked at intermediate altitudes. Intermittent springs hosted fewer taxa than permanent springs, and none of the taxa were exclusive to these springs. No

			oxygen saturation, pH, nutrients, anions, cations metals. Average current velocity. Shannon Diversity. Species richness	significant correlation was found between richness and Shannon diversity index with altitude, the highest values for both were associated with an intermediate altitudinal range. Prudent and conservative land management must assume that all springs need protection to conserve their faunal assemblages.
(Amaral et al. 2021)	Brazil	Native forest vs eucalyptus	Temperature, pH, conductivity, dissolved oxygen, turbidity, depth, total nitrogen, total phosphorus, particle size	There is similarity in EPT functional diversity indices in springs in eucalyptus and forest areas, but the faunal composition and taxonomic richness of EPT were affected by eucalyptus plantations. Greater (native) vegetation cover, greater taxonomic richness and diversity. In eucalyptus areas, springs showed lower genus richness and a different EPT taxonomic composition compared to springs in natural forest areas. The homogenization and reduction of marginal vegetation in eucalyptus areas harm the natural mechanisms of sediment retention, altering the quality of the water and the plant matter supplied to the springs, affecting the benthic fauna.
(Leshosmaa et al. 2018)	Finland	Preserved area, agricultural area, built areas, explored areas	Temperature, pH, conductivity, dissolved oxygen, turbidity, depth, PT, current speed, nitrate, chloride, % of vegetation cover	Lower wealth in the most impacted area. The impacted areas did not differ in wealth. The richness of rarefied taxa of specialist and generalist macroinvertebrates differed between groups of sites, being lower in impacted environments than in natural springs, while the difference between natural sites and those impacted by drainage was not significant. The impacted areas have lower water quality and less wealth. The impacted areas differed from the preserved areas. The taxonomic richness and species composition of benthic macroinvertebrates were compromised by impaired water quality in impacted environments.
(Okon et al. 2020)	Poland	Forest springs X anthropogenic springs	Temperature, pH, conductivity, dissolved oxygen, oxygen	The presence of crenobiotic fauna species in the springs studied is related to the constantly low water temperature and the natural state of the environment. The preserved springs that have the

			saturation, nutrients (minerals)	least anthropogenically altered environment have greater species richness and diversity. Preserved springs had higher levels of ecological significance. Springs with thick sediment showed a greater number of taxa. Springs with more stable flow speeds and less human interference showed greater diversity.
(Rozkowski and Dumnicka, 2010)	Poland	Preserved area X agricultural area	Taxon density	The impacted areas have a lower density of taxa and do not contain species of crenobionts (sensitive). The most common species in karst running waters in the study area was *Gammarus fossarum* (Crustacea), found in all springs studied. The crustacean *Niphargus tatrensis* widely distributed in the groundwater of Poland, in karst and non-karst areas has been found in a small number of springs. *Gianius aquedulcis* was first found in Poland in these springs. Many eurybiont (resistant) species increased in polluted springs, so the density of eurybionts increased with increasing pollution.
(Claret and Marmonier, 2019)	France	Forest x pasture	Temperature, pH, conductivity, dissolved oxygen, oxygen saturation	Pasture areas have less richness compared to preserved areas. Richness and diversity decreased with altitude. Greater abundance and richness in fine sediments. Fine sediments and low nitrate levels controlled the greatest richness and abundance. Benthic macroinvertebrate abundances did not change significantly with elevation, but taxonomic richness was clearly associated with temperature and negatively correlated with elevation in all three habitats studied, species richness (across the three habitat types) and diversity index decreased with elevation, while invertebrate abundance did not change with elevation.
(Ilmonen et al. 2012)	Finland	Preserved X Anthropic (predominance of forestry and pasture)	Temperature, pH, altitude, conductivity	Total macroinvertebrate abundance and crenophile taxa abundance showed large variation between reference and test sites, with higher abundances at reference than test sites. Most locations differ from reference locations. Test sites showed low flow. Taxon richness also showed considerable variation between reference and test sites for macroinvertebrates. Five of the indicator macroinvertebrates were crenophilous species, only the fly *Crunoecia irrorata* (Curtis) was confined to reference sites. Many disturbed springs, but with stronger groundwater flow,

				supported macroinvertebrates similar to the reference condition.
(Knysh et al. 2016)	Canada	Forestry X Agricultural	Temperature, pH, conductivity, dissolved oxygen, oxygen saturation, nutrients (minerals), flow, granulometry	The forest and agricultural springs formed two groups and were statistically different based on the physical and chemical variables of the habitat, where forest habitats were more homogeneous. The richness measure showed greater diversity in forest sites than in agricultural sites. Thienemanniella was the taxon that most contributed to the dissimilarity between springs between the two land use categories. Several invertebrate taxa have been associated with deciduous tree density and habitat heterogeneity (mainly substrate and nitrogen variability). Agricultural activities have increased nutrient production, sediment additions, altered plant communities and habitat structure, in turn altering invertebrate community structure.
(Keleher and Rader, 2008)	USA	Forestry X moderately impacted X severely impacted	Temperature, pH, conductivity, dissolved oxygen, salinity	Large-scale disturbance of boreal springs appears to have had a negative effect at the species level, causing a regional decline in spring-specialized taxa. *Gammarus lacustris* and *Hyalella aztec*a predominated in preserved areas. Two genera of Chironomidae (*Micropsectra* + *Cricotopus*) declined with increasing disturbance. Macroinvertebrate taxomonic composition was separated in ordination space between reference sites and severely impacted test sites across all three classes of impacted sites. *Amphipod* abundance decreased with increasing disturbance in all classes, but was significant only for *H. azteca.*

4 Conclusion

This systematic review revealed the harmful effect of native vegetation suppression and/or replacement of riparian forests, especially by pasture and agricultural areas, on the ecological integrity of springs. The main ecological responses of the benthic community are related to changes in water quality, especially evidenced by increased variables such as electrical conductivity and suspended solids in areas with a higher degree of disturbance. These changes have direct consequences for the benthic fauna, leading to a reduction in the richness and diversity of the community in springs negatively impacted by anthropogenic activities, whether by the impacts of eucalyptus areas, pasture, or agriculture.

Our findings warn of the risk of environmental degradation caused by land use change, leading to the loss of biodiversity in springs, which are crucial for the survival of all biota and mainly for the maintenance of streams and rivers within the drainage basin. Furthermore, the benthic macroinvertebrate community has proven to be a valuable bioindicator for our understanding of the effects of land use change on the diversity and richness of benthic fauna in springs.

Future studies, with other approaches, examining functional diversity and the relationship with different environmental impacts in springs, may provide more evidence of the effects of environmental degradation on the benthic community.

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ARTIGO 2

Does the gradient of environmental degradation affect the macroinvertebrate community in springs?

Versão preliminar para submeter na revista

Studies on Neotropical Fauna and Environment

Does the gradient of environmental degradation affect the macroinvertebrate community in springs?

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Para submeter em *Studies on Neotropical Fauna and Environment*

RESUMO

Mudanças drásticas nos ambientes naturais levam à alteração na comunidade bentônica provocando impactos profundos nos processos ecológicos em nascentes. No presente estudo investigamos o efeito de diferentes usos da terra – efeito de paisagem - (área urbana, pastagem, eucalipto e mata nativa) na estrutura taxonômica e funcional da comunidade de macroinvertebrados bentônicos em habitats nascentes. Para testar se o gradiente de degradação ambiental afeta a diversidade e composição de táxons amostramos a comunidade de macroivertebrados aquáticos em 40 nascentes sob diferentes usos da terra e coletamos amostras de água para análise dos parâmetros físico-químicos. Nossos resultados indicam que os tipos de uso da terra afetaram a estrutura da comunidade de macroinvertebrados. Além disso, encontramos diferentes padrões para os grupos funcionais relacionados com os diferentes tipos de usos da terra. As nascentes em área de mata nativa e eucalipto são mais similares entre si quando comparadas às áreas de pastagem e urbana. Os resultados encontrados corroboram estudos já realizados em gradientes de degradação em escalas locais, regionais e globais.

Palavras-chave: bentofauna; diversidade; grupos tróficos; mananciais.

ABSTRACT

Drastic changes in natural environments lead to alterations in the benthic community, causing profound impacts on ecological processes in springs. In the present study, we investigated the effect of different land use - landscape effect - (urban area, pasture, eucalyptus, and native forest) on the taxonomic and functional structure of the benthic macroinvertebrate community in spring habitats. To test whether the gradient of environmental degradation affects taxon diversity and composition, we sampled the aquatic macroinvertebrate community in 40 springs under different land uses and collected water samples for analysis of physicochemical parameters. Our results indicate that land use types affected the structure of the macroinvertebrate community. Furthermore, we found different patterns for functional groups related to the different land use types. Springs in native forest and eucalyptus areas are more similar to each other compared to pasture and urban areas. The results corroborate studies already conducted on degradation gradients at local, regional, and global scales.

Keywords: benthic fauna; diversity; trophic groups; water sources.

1 Introduction

Healthy ecosystems are essential for the production of ecosystem services; however, natural areas are increasingly under significant threat from anthropogenic activities, which lead to habitat loss and, consequently, the loss of biodiversity (Adla et al., 2022; Rader et al., 2008; Staudacher and Fureder, 2007). Distinctly, soil degradation in recent decades, caused by climate change and the replacement of natural areas with other types of land use, such as monocultures and urbanization, has become one of the most relevant ecological issues on a global scale (Bajocco et al., 2012; Marrochi et al., 2021). These severe changes in the environment create an environmental gradient and trigger drastic responses in biotic communities (Haidvogl, 2018; Von Fumetti and Blattner, 2017). An example is benthic macroinvertebrate communities, which are sensitive to environmental changes, widely used as bioindicators of water quality, and employed as a tool for assessing the ecological health and integrity of aquatic ecosystems (Adesakin, 2023; Mir et al., 2021).

Benthic macroinvertebrates are morphologically and physiologically adapted to distinct environmental conditions and various types of habitats, allowing them to survive in regions under different land uses. Among the morphological characteristics of benthic organisms are body shape and size, which minimize resistance to currents (Buffagni, 2021; Vineetha and Nandan, 2021); attachment structures such as suckers, hooks, and bristles, essential appendages for organisms living in fast-flowing environments (Akinpelu et al., 2024; Glasby et al., 2021); and a respiratory system with gills, common in environments with low oxygenation in the water, facilitating gas exchange (Paz et al., 2022). Physiologically, some macroinvertebrates can adapt to environmental stress conditions, tolerating variations in pH, temperature, and dissolved oxygen (Hamid et al., 2021). Additionally, some groups can reduce their metabolism under hypoxic conditions (Reynaga et al., 2020). These morphophysiological characteristics of benthic organisms are not only fundamental for survival in aquatic environments under different land uses but also make them biological indicators of conserved and degraded areas.

Different types and intensities of disturbances in natural environments create environmental gradients and lead to changes in the benthic community, causing profound impacts on refugia and the types of available food resources, as they alter the quantity and quality of available organic matter, leading to a loss of functional diversity (Juvigny- Khenafou et al., 2021; Stamenkovic et al., 2024). As each trophic group has a distinct and crucial role in springs, the loss of functional redundancy — that is, the ability of different species to perform similar ecological functions — the more redundant they are, the lower the functional richness of the community, that is, lower functional diversity and greater functional equitability (Akamagwuna et al., 2023; Bhat et al., 2022; Guimarães et al., 2024; Liu et al., 2021; Rumschlag et al., 2023). Furthermore, communities with high functional diversity are better able to recover from disturbances and maintain the stability of ecological processes, such as nutrient cycling and energy flow (Leiva et al., 2022). Environmental gradients (Hawkings et al., 2003), as well as biological metrics of benthic communities, have been increasingly discussed in the literature to assess water quality and the integrity of aquatic ecosystems (Akay and Dalkiran, 2020; Orozco-Gonzáles and Ocasio-Torres, 2023; Reiss and Chifflard, 2018; Yorulmaz and Ertas, 2021).

Springs are aquatic environments that are increasingly under significant threat from anthropogenic activities (Batool et al., 2018; Stevens et al., 2021). These environments are globally recognized for their ability to provide ecosystem services and maintain biodiversity (Lopes et al., 2019; Stevens et al., 2021). Changes in land use and occupation in areas surrounding springs have significant impacts on the physical and chemical factors of the water (Bhat et al., 2022). Pasture and monoculture areas can increase erosive processes, leading to increased sedimentation and reduced water flow (Centeri, 2022). The use of fertilizers affects water chemistry, especially by increasing phosphorus and nitrogen concentrations, in addition to introducing herbicides and pesticides (Ramos et al., 2018; Panwar, 2020). In urban areas, soil sealing reduces infiltration and increases surface runoff, making it difficult to retain water in the springs. Furthermore, springs in urban areas frequently receive sewage, which increases the load of nutrients and pathogens, compromising water quality (De Mello et al., 2018; Luo et al., 2020).

Given the above, in this assessment, we investigated the effect of different land uses (urban, pasture, eucalyptus and native forest) on the taxonomic structure and functional feeding groups of benthic macroinvertebrates in spring habitats. We also sought to answer two complementary questions: (1) Do community structure and functional feeding groups differ between springs under different land uses? To this end, we hypothesized: (i) that the gradient of environmental degradation (different land uses) negatively affects the richness, abundance, diversity and composition of taxa; and (ii) that functional feeding groups differ between springs under different land uses and will be greater in conserved areas. (2) Which environmental variables are most strongly associated with different land uses? In relation to this question, we hypothesized that the gradient of environmental degradation alters the physical and chemical factors of water that will show worsening in water quality in more degraded springs, especially urban ones.

2 Materials e Methods

2.1 Study Area

We conducted the study in the Ipanema stream basin in the eastern region of Minas Gerais, within the Atlantic Forest biome, in the municipality of Ipatinga (19º46’36.07‖ S and 42º55’89.57‖ W), Brazil (Figure 1). Ipatinga has a population of 227,731 inhabitants (IBGE, 2022).

The study area has a tropical climate with higher rainfall in the summer than in the winter. According to Köppen and Geiger, the climate is classified as Aw. The average annual temperature recorded in Ipatinga is 28.3ºC, and the annual precipitation is approximately 1,108 mm.

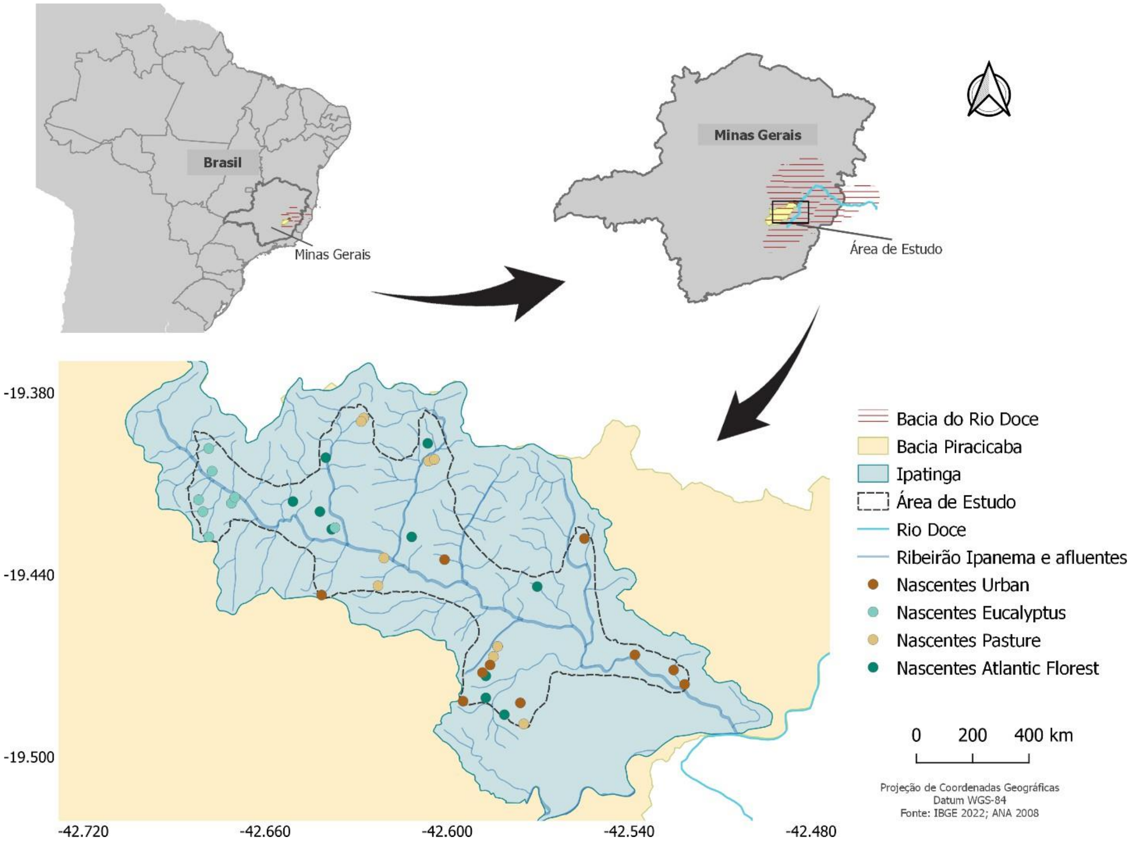

Figura 1 – Location of the sampling points in the Ipanema Stream basin, Ipatinga, MG. Source: (IBGE, 2022; ANA, 2008). Own elaboration.

2.2 Date collection

To test whether the gradient of environmental degradation affects the diversity and composition of taxa, we sampled the aquatic macroinvertebrate community, from July to September 2020, only once, in 40 springs under different land uses: 10 in areas of preserved forest (the historical ecosystem of the region is Atlantic Forest - located in private areas with APP - reference sites); 10 in eucalyptus areas, 10 in pasture areas and 10 in urban areas. The macroinvertebrates were collected in samples of different sediments (stone, sand and leaf litter substrates). We collected sediment samples composed of stone, sand and leaf litter substrates, in each spring in a 5m stretch with a Surber sampler (specially made for collection in springs) with dimensions of 20X20cm, 250µm mesh. Sampling was performed for 15 seconds, totaling 45 seconds in each spring (Amaral et al., 2023). The collected samples were placed in plastic bags and fixed with 70% alcohol and transferred to the laboratory, where they were washed using granulometric sieves with a mesh size of 250 µm. All collected organisms were sorted using a stereoscopic magnifying glass and identified to the family taxonomic level (using specific keys Angrisano, 1995; Carvalho and Calil, 2000; Fernández and Domínguez, 2001; Merritt and Cummins, 1996; Merrit et al., 2014; Mugnai et al., 2010).

To test whether the gradient of environmental degradation affects the functional feeding groups, benthic organisms were classified into functional groups based on the morphological and behavioral adaptations of the organisms to acquire food (Merrit et al., 2017). Based on these criteria, they were classified as: detritivores-shredders, herbivores- shredders, filter-gatherers, collectors-scavengers, scrapers, predators-suckers and predators- swallowers (adapted from Merrit et al., 2017).

To test whether the environmental degradation gradient alters the physical and chemical factors of the water, we collected water samples from each spring at the average depth of the water column, which were stored in polyethylene bottles and kept refrigerated until they were sent to the laboratory for processing and analysis of the water quality variables: Dissolved inorganic nitrogen N_din (mg.L-1), Ammoniacal nitrogen (ammonia) (mg.L-1), Nitrite (NO2-) (mg.L-1), Nitrate (NO3-) (mg.L-1), Total phosphorus (total P-) (mg.L-1), Total solids (st) (mg.L-1), Total dissolved solids (tds) (mg.L-1), Total suspended solids (sts) (mg.L-1), Turbidity (UNT), True color (UNT). Only the analyses performed using a multiparameter water quality probe – YSI were conducted in situ: Electrical conductivity (EC) (µS.cm-1), Dissolved oxygen (DO) (mg. L-1), Oxygen saturation (% sat) (%), pH, Temperature (ºC), Redox potential (ORP) (mV). On the same day of collection, we filtered the samples in the laboratory using a GF-3 fiberglass filter (Macherey Nalgen) for subsequent analyses of dissolved nutrients. An aliquot was removed from the filtration for true color analysis using the Spectroquant Merck NOVA 60 and orthophosphate using the MERCK Phosphate Test kit. We analyzed the turbidity of the raw water using the HACH 2100Q turbidimeter.

The percentage of vegetation cover of each spring was determined using digital photography. We converted the images to black and white and analyzed them using the free software ImageJ (Do Amaral et al., 2023; Rasband, 2012). The result obtained was an average value in pixels, which varied from zero (absence of white area) to 255 pixels (total light input). The values obtained were converted to percentages (Suganuma et al., 2008).

2.3 Statistical Analysis

To assess the sampling efficiency of the collections and identify differences in different land uses, we used the collector curve. To test whether the gradient of environmental degradation affects the diversity and composition of taxa, Generized Linear Models (GLMs) were used. The GLMs had as response variables the richness, abundance, Shannon index, Simpson index and Pielou index and as explanatory variables the different land uses. To compare the composition of the community of benthic macroinvertebrates sampled in springs under different land uses, a Permutational Multivariate Analysis of Variance - PERMANOVA (Anderson, 2001) was performed with the graphical representation obtained from NMDS (Clarke, 1993). To determine the best distribution of the data, a residual analysis was performed.

To test whether the gradient of environmental degradation affects the functional feeding groups, GLMs were also used. The GLMs had as response variables the functional groups of macroinvertebrates and as explanatory variables the different land uses. To determine the best distribution of the data, a residual analysis was performed.

To assess whether the gradient of environmental degradation alters the physical and chemical factors of the water, a Principal Component Analysis (PCA) was performed to determine which physical and chemical factors are most representative for each type of land use. In all tests, p-values <0.05 were considered significant. All statistical analyses were performed using R software (R Core Team, 2024). All test models created for the variables are described in Table 3.

4 Results

A total of 5,714 individuals belonging to 43 taxa were sampled (Table 1). The most frequent families were Chironomidae (1,222 individuals), Ceratopogonidae (426 individuals), and Calamoceratidae (403 individuals). In springs located in Atlantic Forest, eucalyptus, and pasture areas, the families Chironomidae (399, 180, and 215 individuals, respectively), Calamoceratidae (175, 130, and 98 individuals, respectively), and Ceratopogonidae (161, 89, and 87 individuals, respectively) were the most frequent. In contrast, in urban areas, the lowest number of individuals was found (567), with the families Chironomidae (428 individuals), Oligochaeta (122 individuals), and Ceratopogonidae (87 individuals) being the most abundant (Table 1). The percentage of vegetation cover varied from 3.63% to 96.65%. The highest values were recorded in eucalyptus areas, followed by Atlantic Forest, pasture, and urban areas (Table 2, Figure 2).

Table 1. Occurrence of families in different land uses in the Ipanema Stream basin.

Taxa		Atlantic forest	Eucalyptus	Pasture	Urban
Insecta					
	Diptera				
	Ceratopogonidade	161	87	87	89
	Chaoboridae	19	5	11	3
	Chironomidae	399	159	215	428
	Culicidae	136	44	77	82
	Dixidae	13	11	1	1
	Dolichopodidae	17	9	10	9
	Empididae	5	0	0	3
	Musicidae	6	0	55	30
	Psychodidae	35	2	1	0
	Simulidae	36	22	2	0
	Tabanidae	6	1	20	5
	Tipulidae	58	58	19	27
	Odonata				
	Aeshinidae	60	25	8	2
	Coenagrionidae	14	6	1	1

	Corduliidae	11	0	1	0
	Gomphidae	80	58	4	6
	Libellulidae	44	33	1	0
	Coleoptera				
	Dysticidae	24	17	1	10
	Elmidae	71	55	1	6
	Gyrinidae	28	10	13	0
	Lutrochidae	16	10	2	0
	Psephenidae	23	7	1	0
	Trichoptera				
	Calamoceratidae	175	124	98	0
	Glossosomatidae	62	59	11	1
	Helicopsichidae	96	53	0	0
	Hidropsychidae	135	43	5	4
	Hydroptilidae	62	19	2	0
	Leptoceridae	144	59	4	0
	Limnephilidae	131	58	15	0
	Odontoceridae	53	22	14	0
	Ephemeroptera				
	Baetidae	45	65	19	1
	Perlidae	33	34	0	0
	Hemiptera				
	Gerridae	32	14	3	0
	Naucoridae	29	20	3	1
	Vellidae	55	44	14	5
Clitellata					
	Hirudinea	46	27	24	34
	Oligochaeta	45	69	38	122
Gastropoda					
	Ampullariidae	3	2	2	33
	Physidae	2	0	2	4

	Planorbidae	7	1	17	14
Ostreoida	Ostreoida	13	2	8	17
Nematoda	Nematoda	62	3	11	1
Nematomorpha	Nematomorpha	0	0	21	4

Table 2. Mean percentage of vegetation cover in springs under different land uses in the Ipanema Stream basin, MG.

Nascentes	**Uso da terra**	**% Cobertura Vegetal**
N1	Urban	31.32
N2	Urban	35.33
N3	Urban	3.63
N4	Urban	23.16
N5	Urban	39.66
N6	Urban	47.60
N7	Urban	33.85
N8	Urban	56.25
N9	Urban	90.38
N10	Urban	57.69
N11	Eucalyptus	81.77
N12	Eucalyptus	20.62
N13	Eucalyptus	83.28
N14	Eucalyptus	94.11
N15	Eucalyptus	93.75
N16	Eucalyptus	96.19
N17	Eucalyptus	92.36
N18	Eucalyptus	96.56
N19	Eucalyptus	96.65
N20	Eucalyptus	75.59
N21	Pasture	21.01
N22	Pasture	50.35

N23	Pasture	47.95
N24	Pasture	8.46
N25	Pasture	90.86
N26	Pasture	60.59
N27	Pasture	19.73
N28	Pasture	59.28
N29	Pasture	60.59
N30	Pasture	52.67
N31	Atlantic forest	78.60
N32	Atlantic forest	87.09
N33	Atlantic forest	68.94
N34	Atlantic forest	28.92
N35	Atlantic forest	27.03
N36	Atlantic forest	71.41
N37	Atlantic forest	66.09
N38	Atlantic forest	58.39
N39	Atlantic forest	55.77
N40	Atlantic forest	82.06

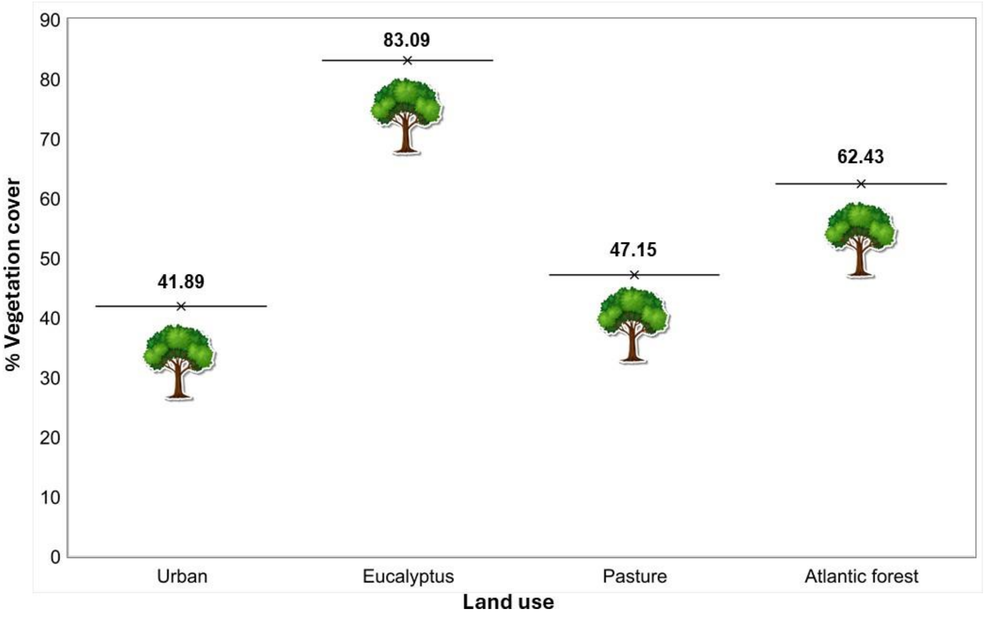

Figure 2. Mean percentage of vegetation cover in springs under different land uses in the Ipanema Stream basin, MG.

The collector's curve indicates that the observed richness for Atlantic Forest and eucalyptus areas already represents the actual richness of these areas, whereas for pasture and urban areas, the richness remains underestimated, as the curve has not yet reached an asymptote and shows a trend toward an increase in the number of taxa. The Atlantic Forest shows the highest richness both in observations and in the extrapolated estimate compared to other land uses, followed by eucalyptus, pasture, and urban areas (Figure 3).

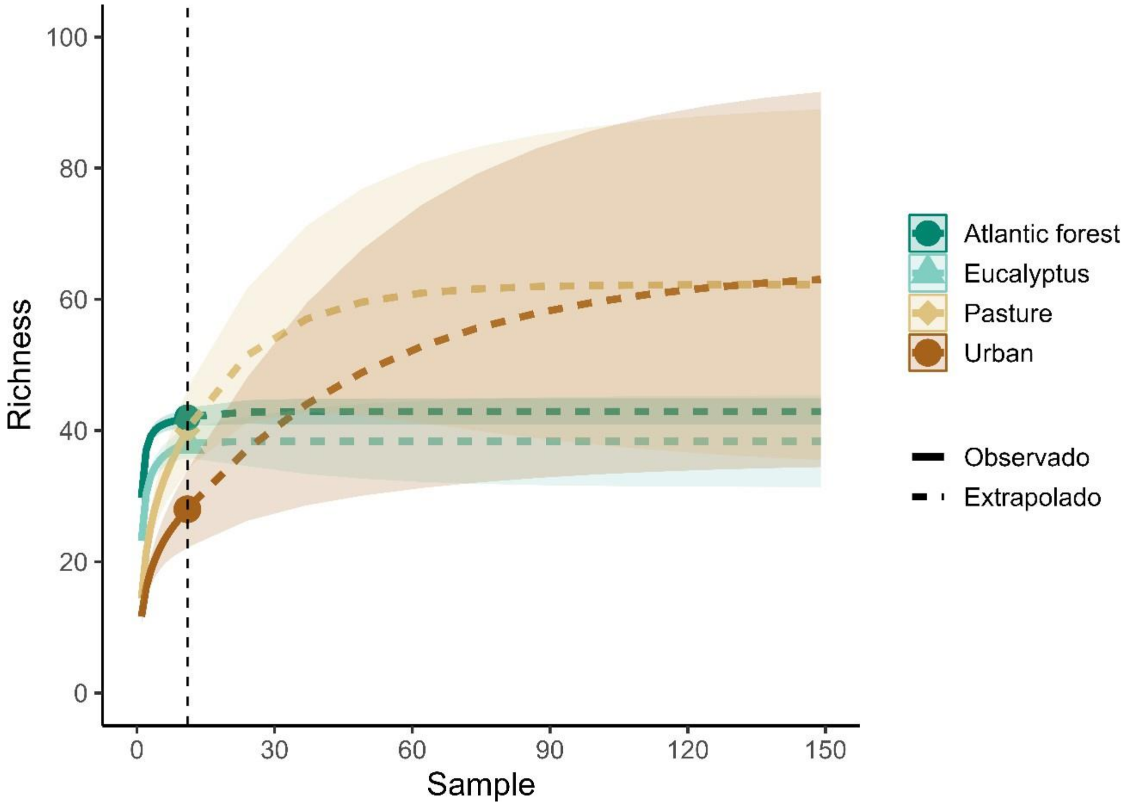

Figure 3. Family accumulation curves using the rarefaction method based on benthic macroinvertebrate sampling in 40 springs of the Ipanema Stream basin. Rarefaction curves (solid lines) and extrapolations (dashed lines) with 95% confidence intervals, representing the number of individuals obtained through the sampling process. The 95% confidence intervals (shaded areas accompanying the lines) were obtained using the randomization method. Reference samples are indicated by colored solid points.

The types of land use significantly affected the richness (Chi = 114.64; $p < 0.005$, Table 3) and abundance (Chi = 43.646; $p < 0.005$, Table 3) of benthic macroinvertebrates. Both metrics were higher in springs located in native forest areas, followed by eucalyptus, pasture, and urban areas (Figure 4). Native forest areas exhibited the highest species richness, followed by eucalyptus, pasture, and urban areas, which had the lowest species richness (Figure 4a). The abundance of individuals was significantly higher in native forest springs compared to other land uses, which were more similar to each other (Figure 4b).

Tabela 3 Modelos dos testes criados para as variáveis analisadas para a comunidade de macroinvertebrados bentônicos em nascentes sob diferentes usos do solo na bacia do ribeirão Ipanema.

Response variables	Explanatory variables	Family	Teste	Df	*Deviance*	p-Value
Richness	Land use	Binomial negativo	Chi=114.64	3	129.908	<0.005*
Abundance	Land use	Binomial negativo	Chi= 43.646	3	84.699	<0.005*
Shannon	Land use	Gaussian	F=32.055	3	8.494	<0.005*
Simpson	Land use	Gaussian	F=9.9042	3	0.23105	<0.005*
Pielou	Land use	Gaussian	F=4.7193	3	0.1302	p=0.0070*
Family composition	Land use	Gaussian	F=5.4374	3		p<0.0001*
Shredder-detritivore	Land use	Binomial negativo	Chi=25.599	3	69.379	p<0.0001*
Herbivorous shredder	Land use	Binomial negativo	Chi=29.816	3	60.751	p<0.0001*
Filter-collector	Land use	Binomial negativo	Chi=91.001	3	135.08	p<0.0001*
Collector-scavenger	Land use	Binomial negativo	Chi=10.211	3	51.780	p<0.0168
Scraper	Land use	Binomial negativo	Chi=34.072	3	78.794	p<0.0001*
Swallowing predator	Land use	Binomial negativo	Chi=146.23	3	198.196	p<0.0001*
Sucking predator	Land use	Binomial negativo	Chi=19.264	3	57.265	p=0.0002*

Caption: * statistically significant values.

The types of land use also affected the diversity of the benthic macroinvertebrate community in the sampled environments. Differences were found in the Shannon index (H’) (F = 32.055; p < 0.005; Table 3), Simpson index (D) (F = 9.9042; p < 0.005; Table 3), and Pielou’s evenness index (J) (F = 4.7193; p < 0.0070; Table 3) according to different land uses. Springs in native forest and eucalyptus areas exhibited higher diversity (H’) compared to pasture and urban areas (Figure 4c). Simpson diversity (D) was higher in native forest and eucalyptus springs compared to pasture and urban areas, which had lower diversity and were more similar to each other (Figure 4d). Pielou’s evenness index (J) was also higher in native forest and eucalyptus areas, indicating greater species uniformity in these areas compared to pasture and urban areas, which showed lower species uniformity and dominant species (Figure 4e).

The composition also differed among land uses (F = 5.4374; p = 0.001; Figure 4f). Springs in native forest and eucalyptus areas were more similar to each other compared to pasture and urban areas. Additionally, there was less variability in family composition in native forest areas, whereas pasture areas exhibited distinct and more variable family compositions (Figure 4f).

For all functional groups, there were differences among the various land uses, with Atlantic Forest areas showing the highest functional diversity, followed by eucalyptus plantations (Table 3; Figure 5). Regarding the detritivore-shredder trophic group, native forest exhibited the highest abundance, followed by eucalyptus, pasture, and urban areas (Figure 5a). For the herbivore-shredder group, pasture and urban areas showed lower abundance and were more similar to each other (Figure 5b). The functional group of filter-collectors was more abundant in springs in native forest areas compared to other land uses (Figure 5c). Native forest also had the highest abundance of scrapers, followed by eucalyptus, pasture, and urban areas (Figure 5d). Predator-ingestors had the highest abundance in native forest areas, greater than in other land uses (Figure 5e). Predator-suckers were most abundant in native forest, significantly differing from urban areas, while eucalyptus and pasture did not differ significantly from either Atlantic Forest or urban areas (Figure 5f).

The Principal Component Analysis (PCA) explained 49% of the variation considering 16 physical and chemical water variables. PCA axis 1 accounted for 31% of the data variance, with the most significant variables being electrical conductivity, ammonia nitrogen, nitrate, nitrite, nitrogen, and total dissolved solids. Axis 2 explained 18% of the variance, with turbidity, color, and total solids as the most significant variables (Figure 6). For Atlantic Forest areas, the most representative vectors were total phosphorus, dissolved oxygen (DO), DO saturation, and temperature. PCA further showed that nitrogen forms were predominant in urban areas with low oxygen levels.

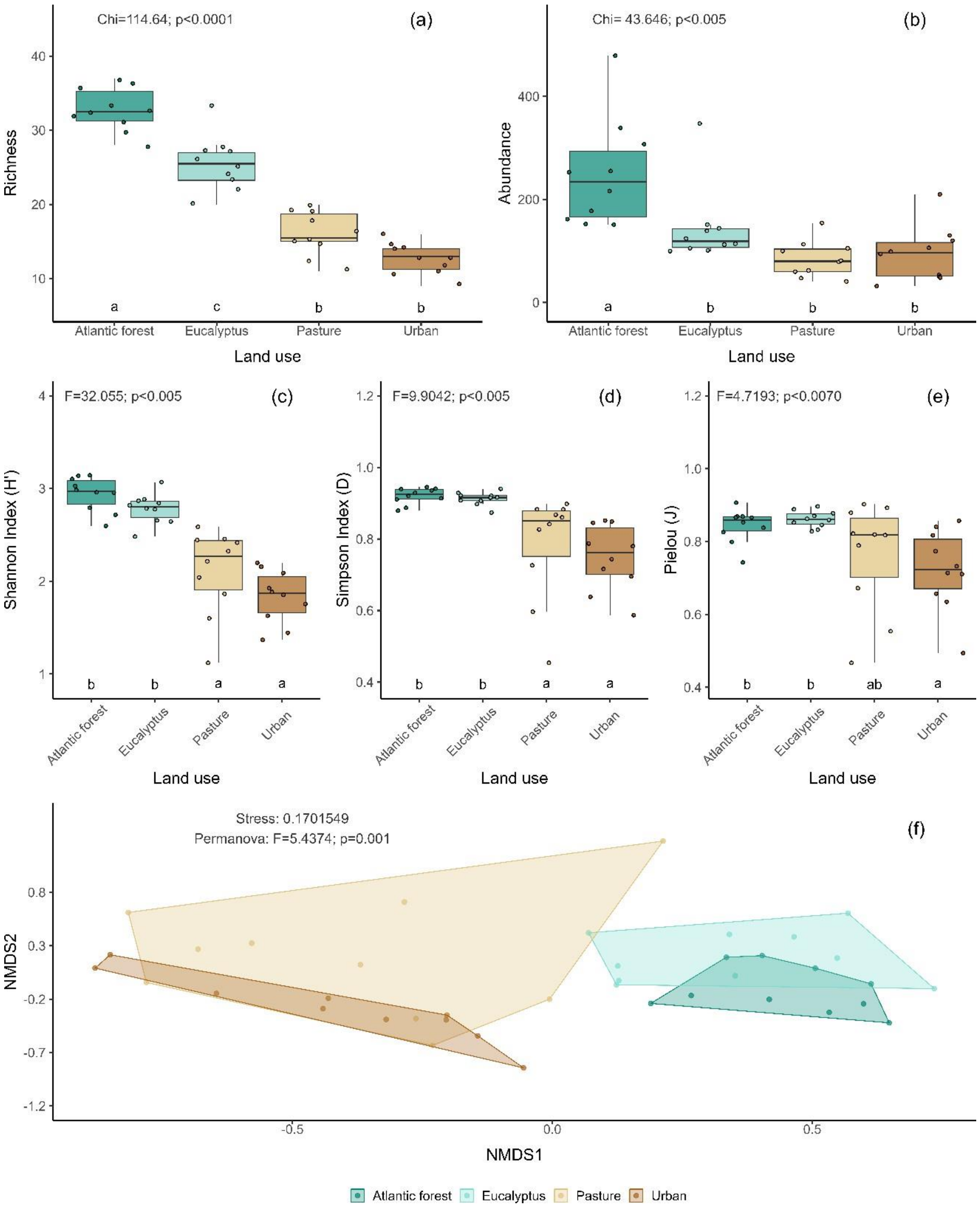

Figure 4. Structure of the macroinvertebrate community in the Ipanema Stream basin under different land uses. (a) Richness; (b) Abundance; (c) Shannon Index; (d) Simpson Index; (e) Pielou’s Evenness Index; (f) Family Composition.

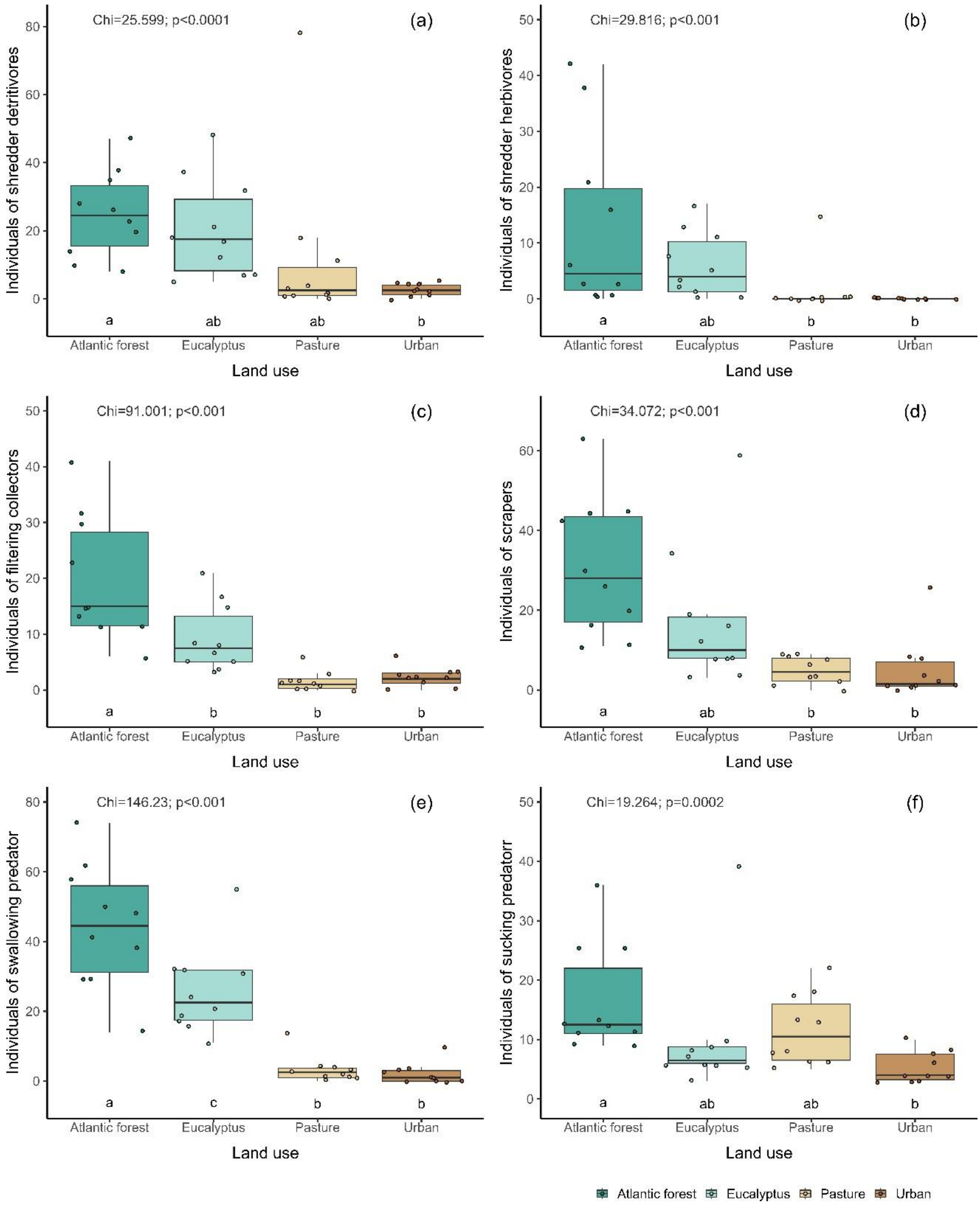

Figure 5 – Functional diversity of benthic macroinvertebrates in springs under different land uses in the Ribeirão Ipanema basin.

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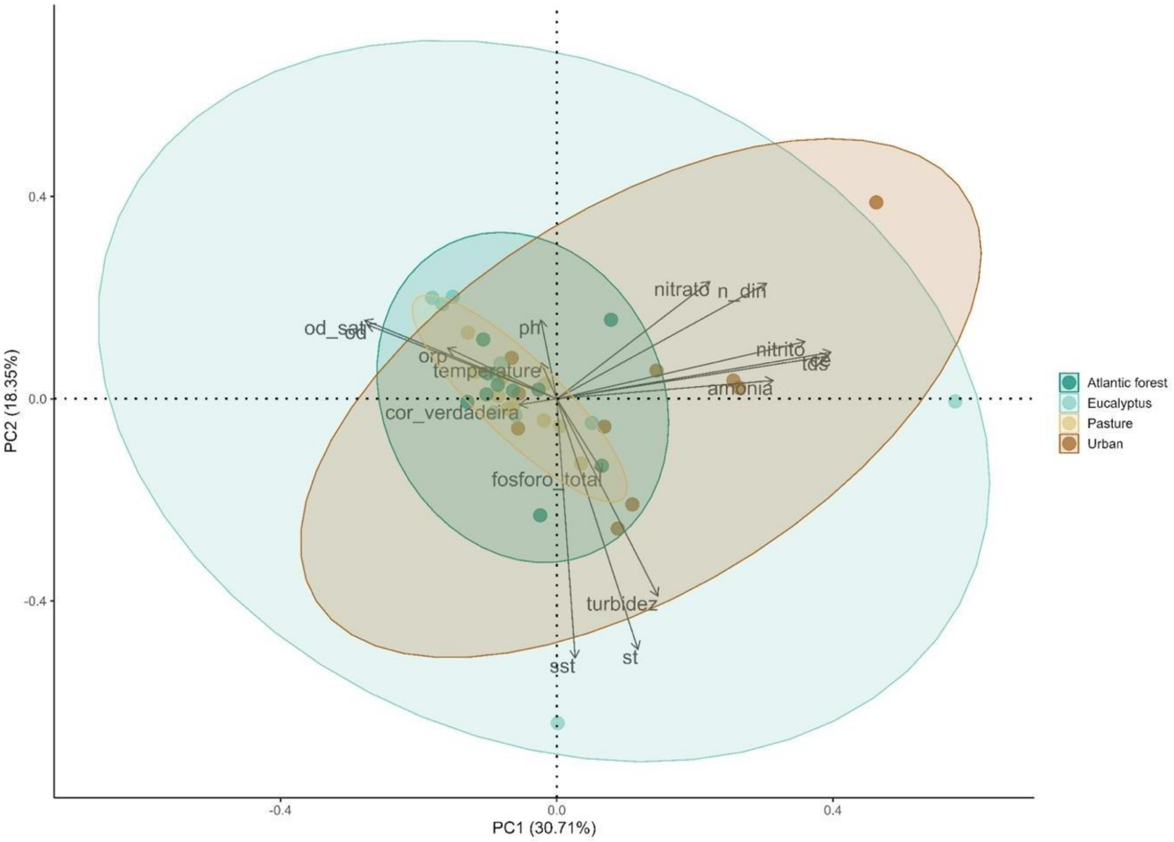

Figure 6 – Principal Component Analysis (PCA) of the physical and chemical factors of water samples from the Ribeirão Ipanema basin under different land uses. Legend: OD – Dissolved Oxygen, OD-sat – Oxygen Saturation, orp – Redox Potential, Temperature, pH, True Color, Total Phosphorus, Turbidity, st – Total Solids, sst – Suspended Solids, tds – Total Dissolved Solids, CE – Electrical Conductivity, N-ammoniacal – Ammonia, Nitrite, Nitrate, N-din – Dissolved Inorganic Nitrogen.

5 Discussão

Our results demonstrated that the taxonomic and functional structure of macroinvertebrate communities responded to the environmental degradation gradient, particularly urbanization, corroborating the hypotheses of this study. However, an intriguing finding was the similarity in community responses between land uses in Atlantic Forest and Eucalyptus areas. A probable explanation for this response could be that a significant portion of the forestry areas are located in buffer zones with the presence of Permanent Preservation Areas (APP). Due to their similarity and proximity, these areas may share very similar responses, which could indicate an adult flow in a source-drain scenario. Additionally, the Atlantic Forest and Eucalyptus areas resembled each other regarding the percentage of vegetation cover.

The loss in richness and abundance in degraded areas, especially in urban springs followed by pastures, recorded in this study, is considered a strong indicator of anthropogenic activities that degrade water quality and consequently have negative impacts on benthic macroinvertebrate communities (Lehosmaa et al., 2018). A study by Sada et al. (2005) on 45 springs in the U.S. evaluated how varying degrees of degradation impact the benthic community. Another study by Patang et al. (2018) showed that anthropogenic impacts led to low diversity indices with the predominance of *Chironomus sp*. and *Melanoides tuberculata*, organisms that are bioindicators of degraded environments. In that study, neither elevation nor water temperature had a significant effect on species richness, emphasizing soil degradation as a determining factor. Similar results were found in our study, where the highest richness of benthic macroinvertebrates was recorded in preserved springs.

In addition to richness and abundance, diversity indices (Shannon, Simpson, and Pielou's Evenness) are also strongly associated with changes in land use, with significant results in impacted and polluted streams (Reiss and Chifflard, 2018; Von Fumetti and Nagel, 2012). Our results demonstrate that the highest diversity indices were recorded in native forest areas, followed by eucalyptus, pasture, and urban areas, corroborating similar research on water quality in springs (Okon et al., 2020; Rokowski and Dumnicka, 2010). Voelz et al. (2005) showed a decline in benthic macroinvertebrate diversity in urban streams located on the eastern slope of the Rocky Mountains in Colorado, USA, compared to reference areas. The findings revealed that after the stream entered urban areas, the reference conditions identified downstream were not recovered along the river's course. The study also found a relationship between urban land use and the physicochemical quality of water, which was reflected in the macroinvertebrate assemblages in both monitored rivers.

In degraded areas, it is also common to observe an increase in the abundance of resistant species due to the availability of nutrients and the lack of predators, as diversity is lower in these areas which have fewer species, and those present have morphophysiological adaptations to withstand pollution and/or reduced water quality (Li et al., 2019). An increase in the abundance of taxa classified as pollution-resistant, such as *Syrphidae, Psychodidae, Culicidae, Chironomidae, Hirudinidae, Lymnaeidae*, *Bulinidae, Tubificidae,* and *Naididae*, was recorded in a study by Tampo et al. (2021) in the Zio River in Togo, revealing that areas with high levels of ammoniacal nitrogen and low concentrations of dissolved oxygen affect the benthic fauna. Our study recorded pollution-resistant taxa such as *Oligochaeta* and *Ampullariidae* with higher abundances in urban areas. These groups are frequently reported as bioindicator organisms in environments with high concentrations of organic matter and low oxygenation of the water (Callisto et al., 2019).

A study by Ilmonen et al. (2012) showed that even reference springs might have been affected by some degree of disturbance - the legacy of past land use (Hardigin et al., 1998). Research by Voelz et al. (2005) indicates that more robust results were generally observed when regional reference data were used and that although reference sites might be partially degraded due to land use impacts, urban areas affect benthic macroinvertebrate assemblages more than other land uses. This study further demonstrated that even using only upstream reference sites in both rivers analyzed, urban areas indicated negative impacts on the benthic fauna, such as biodiversity loss. In our study, the springs in Atlantic Forest areas (reference sites) were located on private properties with APP (Legal Reserves); however, the surrounding areas did not necessarily maintain forest cover. This evidence may be a relevant factor in the similarity of species composition between conserved areas (native forest) and eucalyptus areas with APP, which recorded the highest values of vegetation cover percentage.

Our results show that the abundance of functional groups was higher in Atlantic Forest and eucalyptus areas and consistently lower in pasture and urban areas, representing a conservation gradient. Despite differences in taxonomic diversity, a study by Amaral et al. (2021) in Atlantic Forest and eucalyptus plantation areas in springs in southeastern Brazil demonstrated that the functional diversity indices used were not significantly different between forested and eucalyptus-cultivated areas. These findings are similar to those in our study, which showed that functional diversity was similar between native forest areas and eucalyptus plantations. This fact may be related to the greater environmental heterogeneity present in native forest areas and eucalyptus areas with APP, which provided more diverse allochthonous organic matter, reflecting in higher benthic richness, abundance, and diversity. Although at times native areas showed metrics close to those of eucalyptus areas, the quality and diversity of food resources, as well as refuges provided by native areas, may reflect the higher ecological integrity of the benthic macroinvertebrate community in springs with higher metrics of taxonomic and functional diversity.

The PCA analysis was effective in distinguishing the type of anthropogenic impact on the springs of the Ribeirão Ipanema, particularly urban occupation. The high levels of nitrogen forms recorded in the more degraded environments highlight the importance of monitoring nitrogen forms and other ions for water quality assessment, despite classical eutrophication indices considering only total phosphorus (P-total). The influence of nitrogen forms was also evidenced by a study conducted by Leshomaa et al. (2018), which evaluated anthropogenic impacts on macroinvertebrate, bryophyte, fungal, and bacterial communities in 20 springs in southern Finland, comparing reference and disturbed sites. This study showed that nitrate concentrations were, on average, 30 times lower in reference sites compared to impacted springs. Another study conducted in the Ribeirão Ipanema basin demonstrated strong positive correlations between increased ammoniacal nitrogen and electrical conductivity due to high sewage discharge in water sources from urbanization effects, showing that water quality is strongly related to land use (von Ruckert et al., 2024). The PCA results, therefore, highlighted the importance of including nitrogen forms among the variables assessed in monitoring programs, providing support for proper water resource management.

Our study revealed that the good conservation status of natural vegetation, specifically the Atlantic Forest (original biome) around the springs, influenced the composition, taxonomic, and functional diversity of the benthic macroinvertebrate community, with higher metrics for these areas. As previously mentioned, the greater environmental heterogeneity present in native forest areas, as well as more varied food resources, may be determining factors in the benthic community structure in springs. In streams located in the Hanjiang River basin in China, a study showed that heterogeneous environments (substrate) in natural areas provide, in addition to food resources, refuges for organisms, thereby protecting the benthic community from disturbances. The findings of this study also revealed that vegetation removal around streams in agricultural and urban areas altered substrate composition, increased nutrient input, and played an important role in regulating community structure. This alteration impacted benthic community composition, resulting in higher diversity and a greater presence of predators and organisms with branchial respiration in natural areas (Liu et al., 2021).

In conclusion, our results showed that taxonomic composition and functional diversity differed among the different types of land use (replacement of natural vegetation with eucalyptus, pasture, and urban areas), suggesting that this approach is a powerful tool for monitoring and assessing the environmental impacts of land-use changes on benthic macroinvertebrates in springs. Future studies that evaluate the effects of management practices, particularly harvesting and post-harvesting in eucalyptus areas, can help to understand the real impacts of forestry on springs and aid in the improvement of management plans for these areas. Additionally, comparative studies in springs located in eucalyptus areas with and without riparian buffer zones (APPs) can provide new insights and help elucidate questions about the role of riparian buffer zones in springs. Future investigations may include metacommunity ecology studies that evaluate niche-based and dispersal-related processes, which can help to understand the dynamics of benthic fauna in springs and expand knowledge about the role of environmental filters and spatial factors in structuring benthic communities in springs.

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TERCEIRA PARTE

DIVULGAÇÃO CIENTÍFICA

DIVULGAÇÃO CIENTÍFICA

A divulgação científica desta tese teve início em 2022 quando resultados parciais das análises começaram a surgir. A comunidade escolar do municipio, bem como, os proprietários que autorizaram as coletas em suas áreas, solicitaram informações sobre os resultados das coletas realizadas pelo projeto. A partir daí algumas atividades na comunidade começaram a ser realizadas, como palestras e oficinas. Além disso, percebemos a necessidade de intervenção em algumas nascentes e iniciamos ações socioambientais de recuperação das nascentes com plantio de mudas. Ao longo desse tempo, diversas intervenções estão sendo realizadas e algumas delas estão registradas nos links a seguir. Além da divulgação científica a tese tem como produto um mini book ―Conhecer para conserver: a bacia do Ribeirão Ipanema‖.

Produto da tese - Mídia e Divulgação Científica

https://drive.google.com/file/d/19rXbSAjjQMNBRwW5_bGahYS7g34xlsHk/view?usp=sharing

Site do projeto Nascentes do Ipanema com a produção

Início | Nascentes Do Ipanema

Divulgação científica e mídias regionais

- **Audiência Pública Meio Ambiente** (Apresentação do Projeto Nascentes do Ipanema – 42:48 à 57:48 minutos)

Audiência Pública - Meio Ambiente (youtube.com)

- **Mídias Regionais**

DIÁRIO DO AÇO - JORNAL VIRTUAL (diariodoaco.com.br)

Projeto 'Nascentes do Ipanema' realiza ações para Dia Mundial da Água | Portal Diário do Aço (diariodoaco.com.br)

Professora de Biologia no Vale do Aço é premiada por projeto desenvolvido com alunos | Portal Diário do Aço (diariodoaco.com.br)

PRODUTO DA TESE – DIVULGAÇÃO CIENTÍFICA

Conhecer para conservar:
A bacia hidrográfica do Ribeirão Ipanema

Apresentação

Conhecer para conservar: a bacia do Ribeirão Ipanema” é uma obra que transcende a sala de aula e os muros da escola. Meu objetivo principal é despertar no leitor o sentimento de pertencimento e cidadania. Os estudantes são agentes multiplicadores do saber, e como tal, levarão às famílias e à comunidade em geral, informações científicas de qualidade sobre a realidade ambiental da bacia do Ribeirão Ipanema, localizada no município de Ipatinga, MG. Ações práticas e participação ativa de cidadãos, concretizam-se a partir da educação. A formação de cidadãos atuantes em ações de conservação e recuperação ambiental são efetivas por meio de conhecimentos e consciência técnico-científica para formação de uma sociedade sustentável. Como uma linguagem simples, objetiva e acessível, o texto da presente obra tem uma linguagem explicativa e didática acerca das características e da qualidade hídrica, com dados inéditos da bacia do Ribeirão Ipanema. Embasada na BNCC, a Base Nacional Comum Curricular, a presente obra apresenta conceitos sobre bacia hidrográfica, unidades de conservação, ciclo da água, mudanças de estado físico da água, influência do uso, ocupação e degradação do solo na qualidade da água e organismos bioindicadores ambientais. Aqui, o leitor encontrará informações científicas que despertam o encantamento e o interesse pelas questões ambientais, tão emergentes na nossa região e no mundo. Desejo uma leitura instigante e transformadora!

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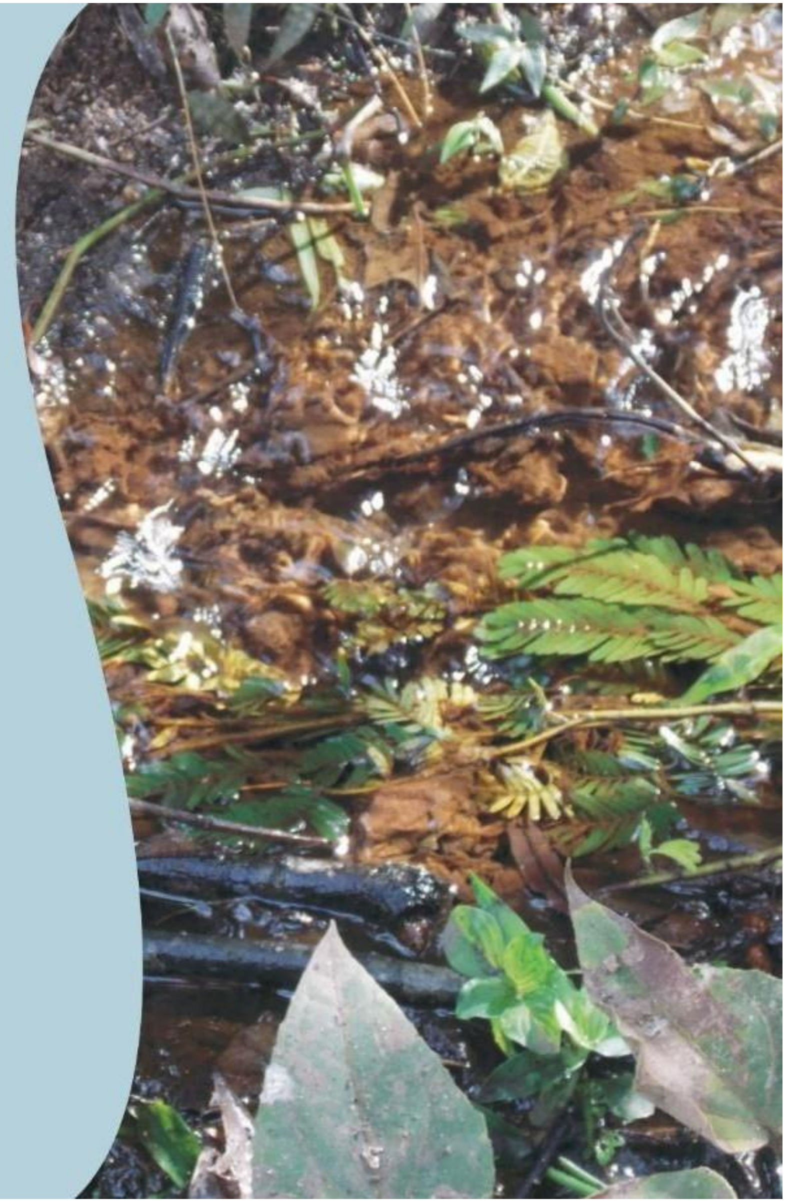


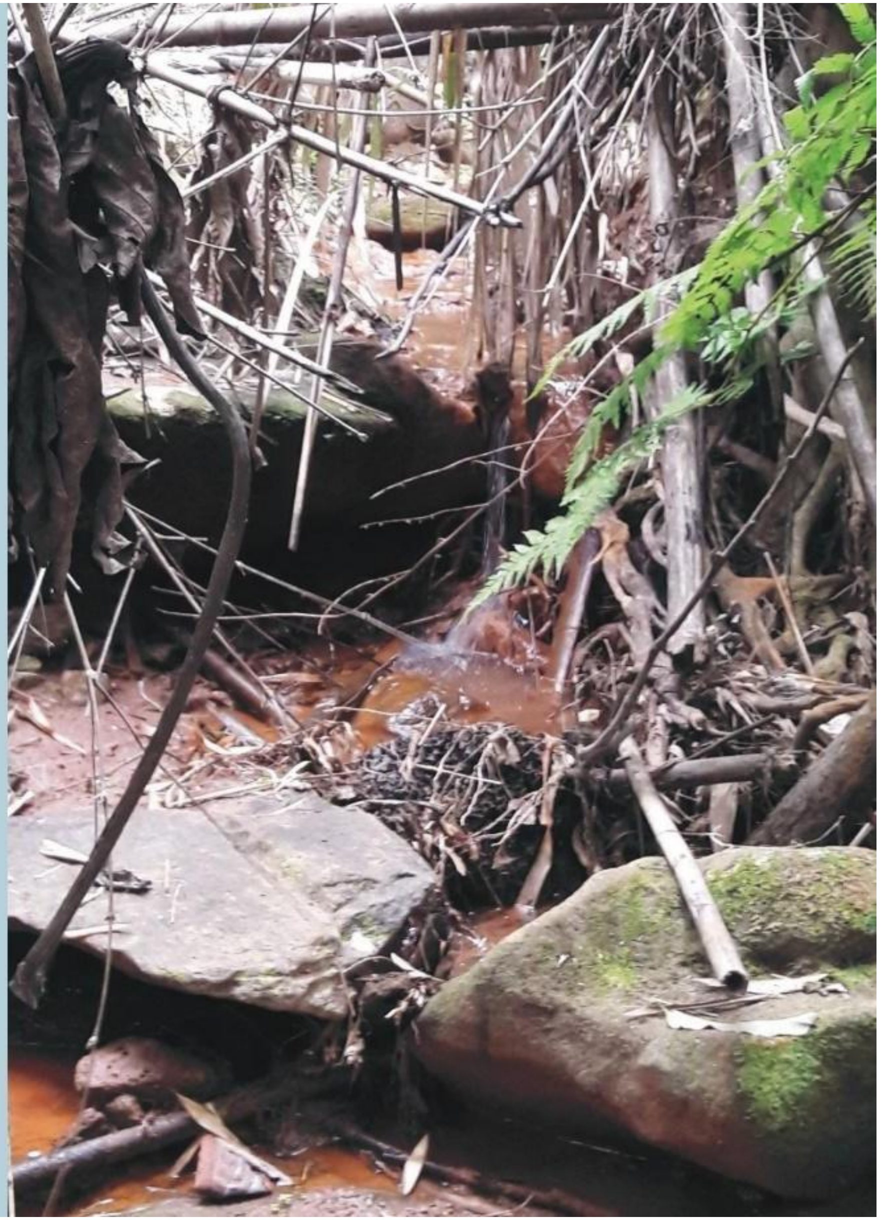
A bacia hidrográfica do Ribeirão Ipanema

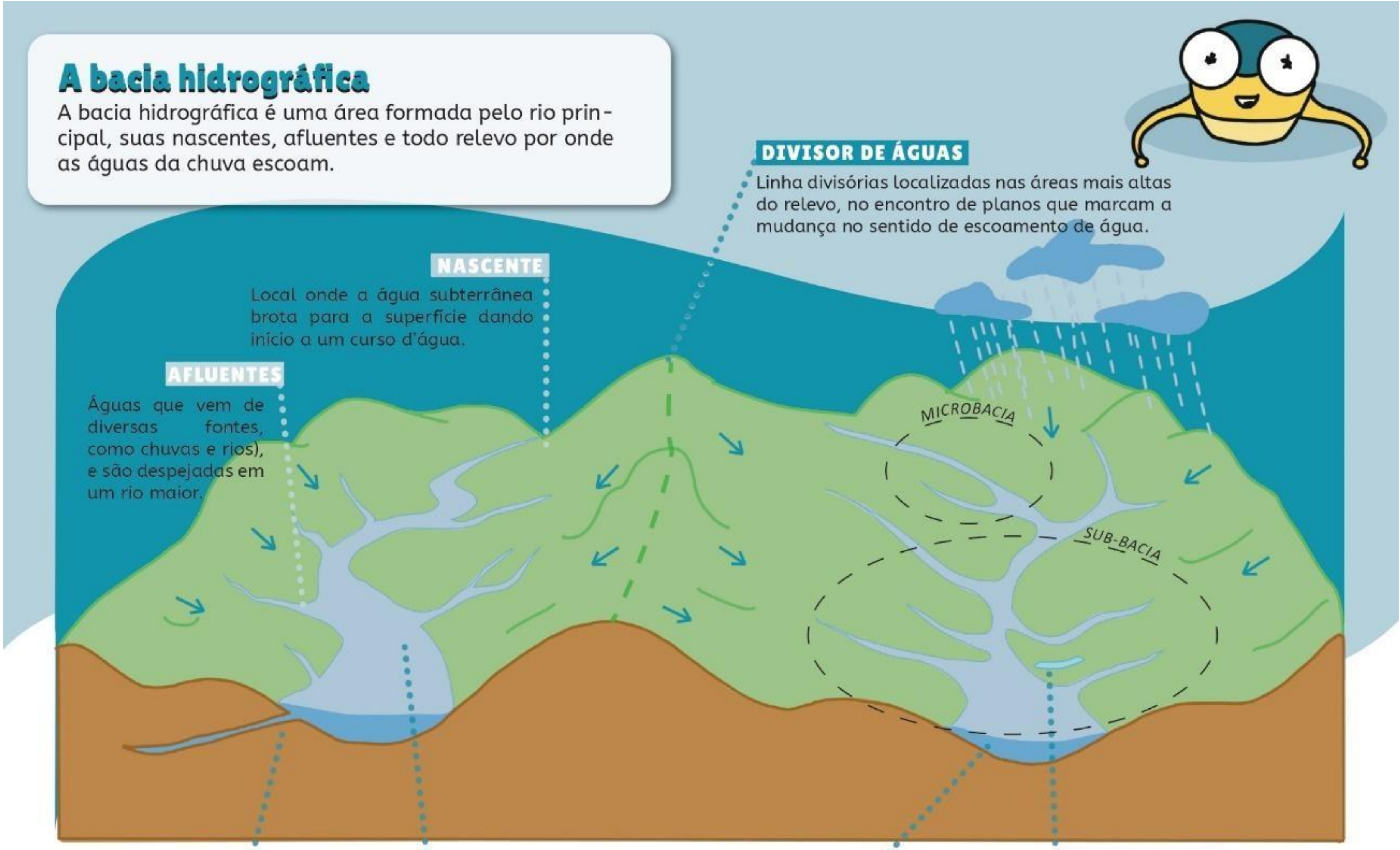
A bacia hidrográfica do Ribeirão Ipanema possui um percurso de 28,5 quilômetros de extensão, drenando uma área de 145 km2, o que equivale a cerca de 87,2% da área total do município, até desaguar no Rio Doce.

Os principais afluentes do Ribeirão Ipanema são os córregos Ipanemão, Ipaneminha, Taúbas, Tribuna, Pedra Branca, Morro Escuro, Madalena, Forquilha, Córrego Novo e Bom Jardim.

O Sistema Nacional de Unidades de Conservação da Natureza (SNUC) foi instituído pela Lei 9.985 de 18 de julho de 2000. As unidades de conservação integrantes do SNUC dividem-se em dois grupos, com características específicas e objetivos distintos: I - Unidades de Proteção Integral: preservar a natureza, sendo admitido apenas o uso indireto dos seus recursos naturais; II - Unidades de Uso Sustentável: compatibilizar a conservação da natureza com o uso sustentável de parcela dos seus recursos naturais.

No Vale do Aço e região, existem muitas unidades de conservação. O PERD - Parque Estadual do rio Doce, uma unidade de proteção integral e unidades de uso sustentável como a RPPN - Reserva Particular do Patrimônio Natural Fazenda Macedônia, RPPN Fazenda do Zaca e APA - Área de Proteção Ambiental Ipanema, onde se localiza a bacia hidrográfica do Ribeirão Ipanema.





A bacia hidrográfica

A bacia hidrográfica é uma área formada pelo rio principal, suas nascentes, afluentes e todo relevo por onde as águas da chuva escoam.

DIVISOR DE ÁGUAS

Linha divisórias localizadas nas áreas mais altas do relevo, no encontro de planos que marcam a mudança no sentido de escoamento de água.

NASCENTE

Local onde a água subterrânea brota para a superfície dando início a um curso d'água.

AFLUENTES

Águas que vem de diversas fontes, como chuvas e rios), e são despejadas em um rio maior.

LENÇOL FREÁTICO

Conjunto de águas que se depositam naturalmente no subsolo.

LEITO PRINCIPAL

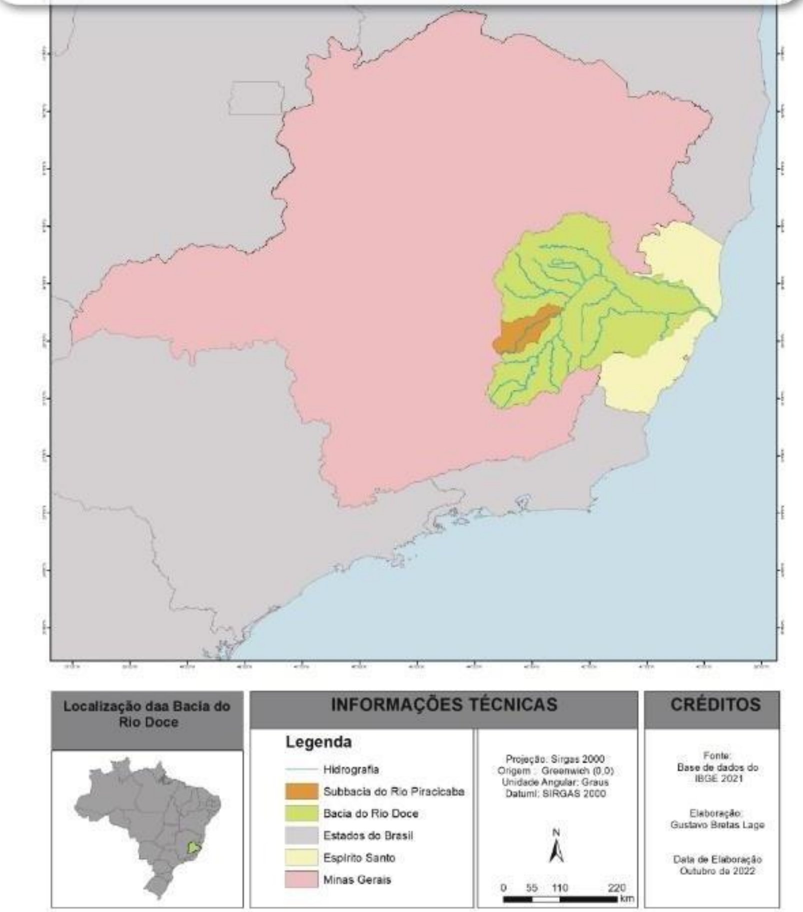
FOZ

FUNDO DE VALE

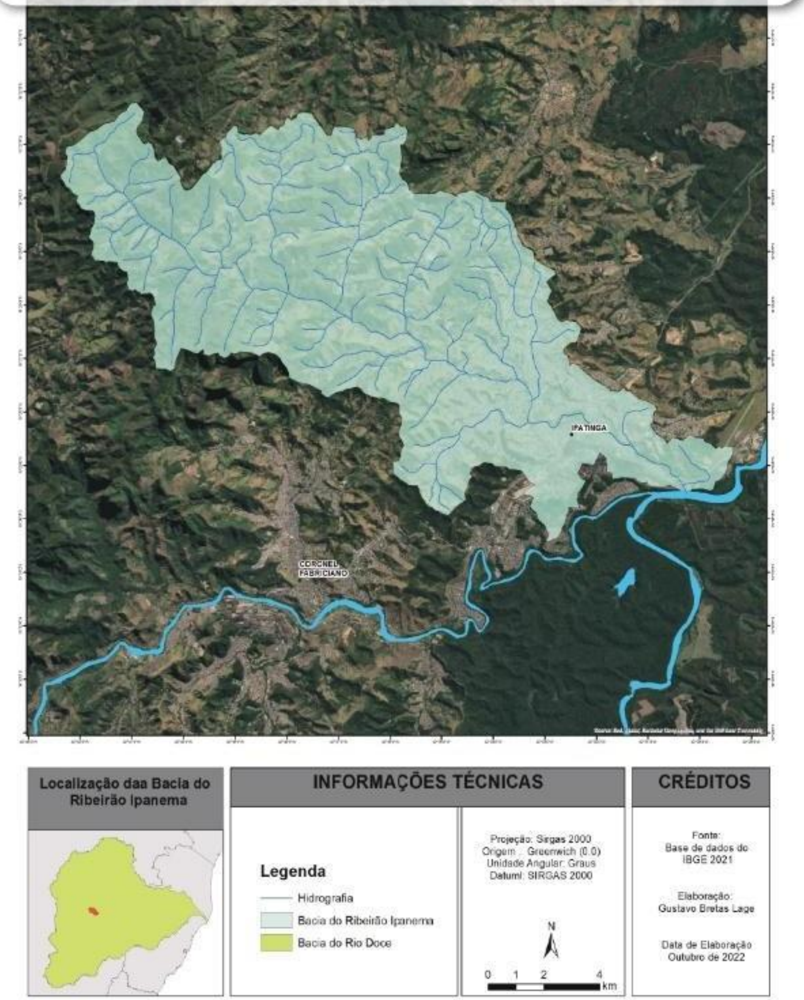
Áreas próximas aos rios e córregos que geralmente sofrem inundações.

Mapa das bacias hidrográficas do Rio Piracicaba e Rio Doce

A bacia hidrográfica do Ribeirão Ipanema está localizada no leste de Minas Gerais, compondo um curso d'água que nasce e deságua no município de Ipatinga, MG.



Mapa da bacia do Ribeirão Ipanema



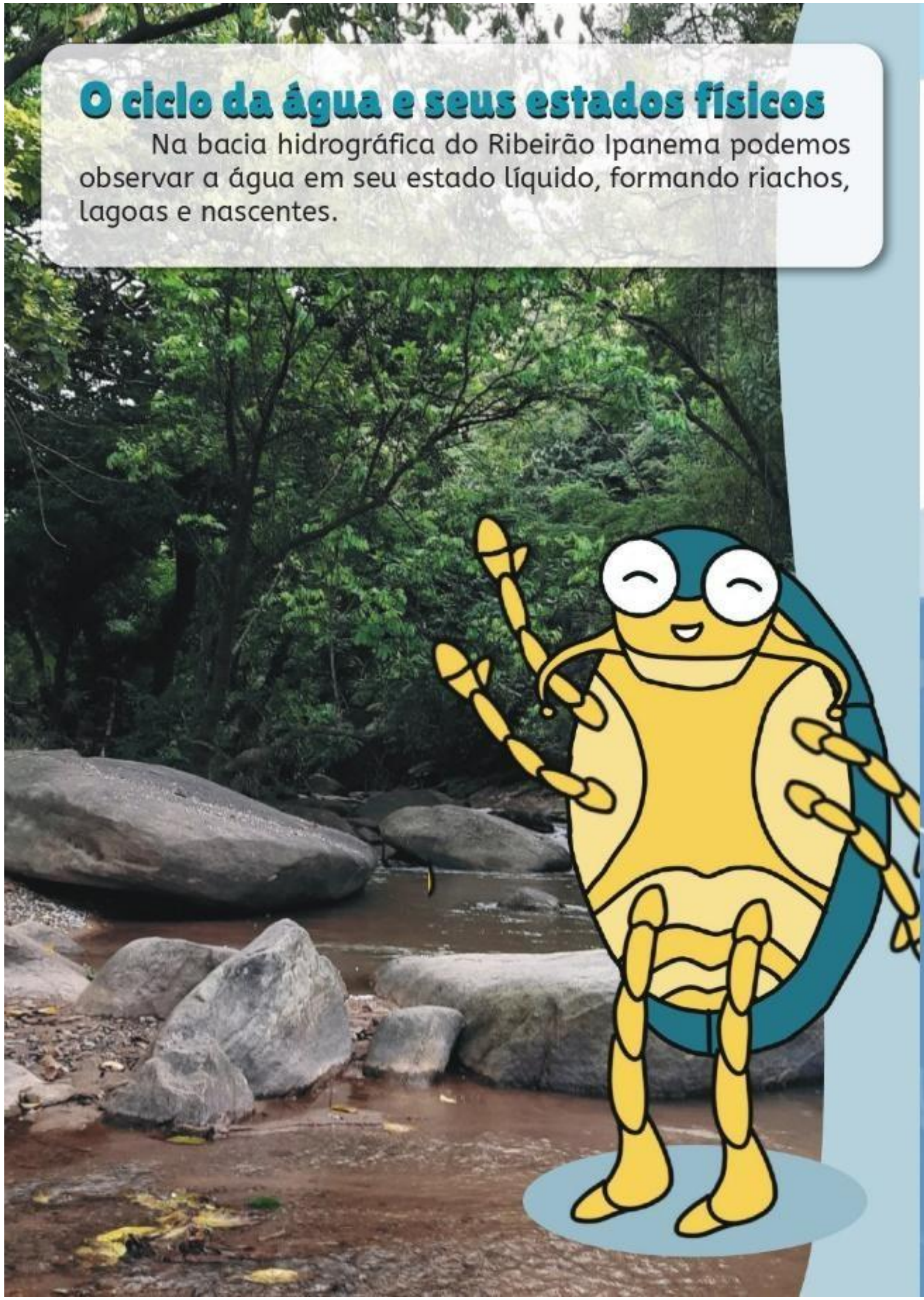
O Ribeirão Ipanema e suas nascentes

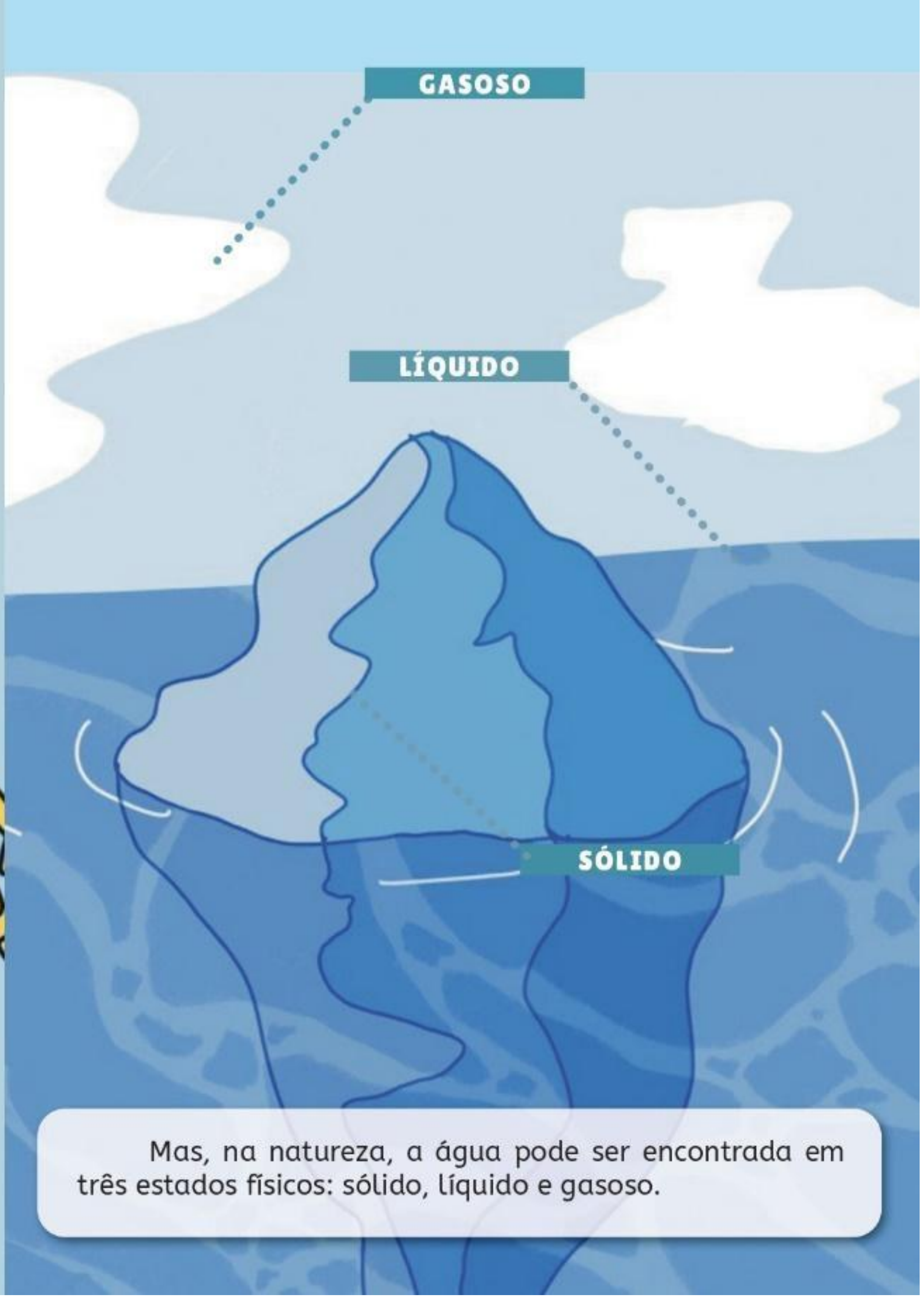
Na bacia do Ribeirão Ipanema foram mapeadas mais de 500 nascentes. As nascentes são os locais onde a água subterrânea “brota” e chega à superfície, formando os chamados olhos-d’água ou mananciais.

As nascentes são, portanto, os locais onde os rios e riachos iniciam seu curso, e, por esse motivo, são consideradas importantes unidades para sobrevivência das espécies, para manutenção dos cursos hídricos, além de fornecerem água para o consumo humano.

O ciclo da água e seus estados físicos

Na bacia hidrográfica do Ribeirão Ipanema podemos observar a água em seu estado líquido, formando riachos, lagoas e nascentes.

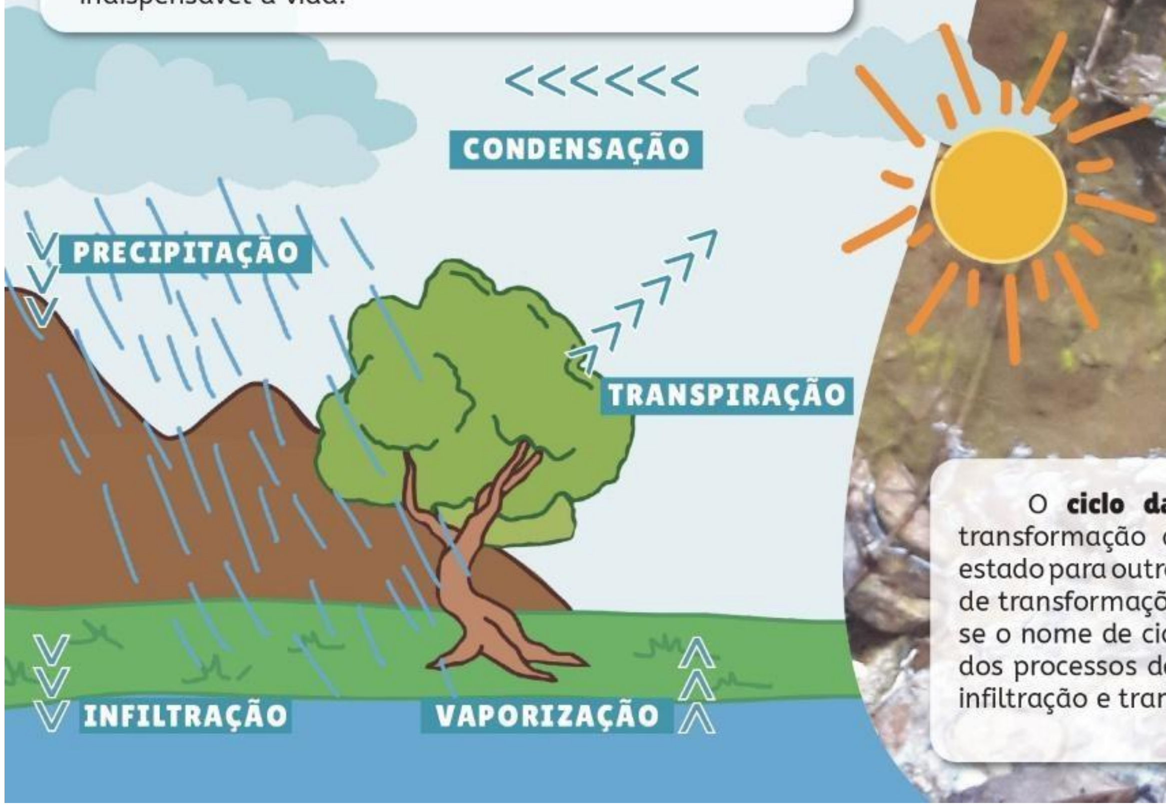




Mas, na natureza, a água pode ser encontrada em três estados físicos: sólido, líquido e gasoso.

E então, como a água pode se apresentar na natureza nos três estados físicos (sólido, líquido e gasoso) ao mesmo tempo?

A água é encontrada na natureza e está distribuída nos rios, lagos, mares, oceanos e em camadas subterrâneas do solo, em geleiras e até mesmo dentro do corpo dos seres vivos como animais, plantas, fungos e, por isso, é indispensável à vida!

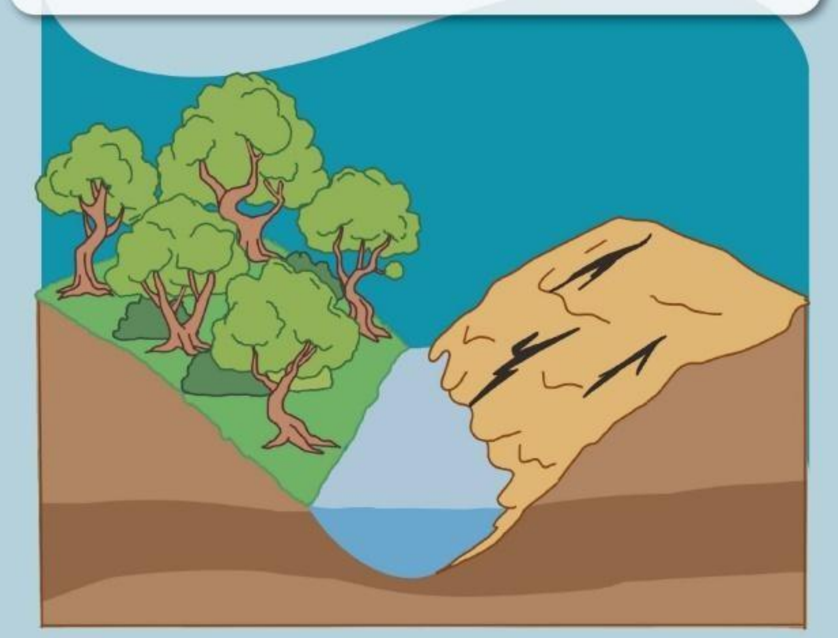


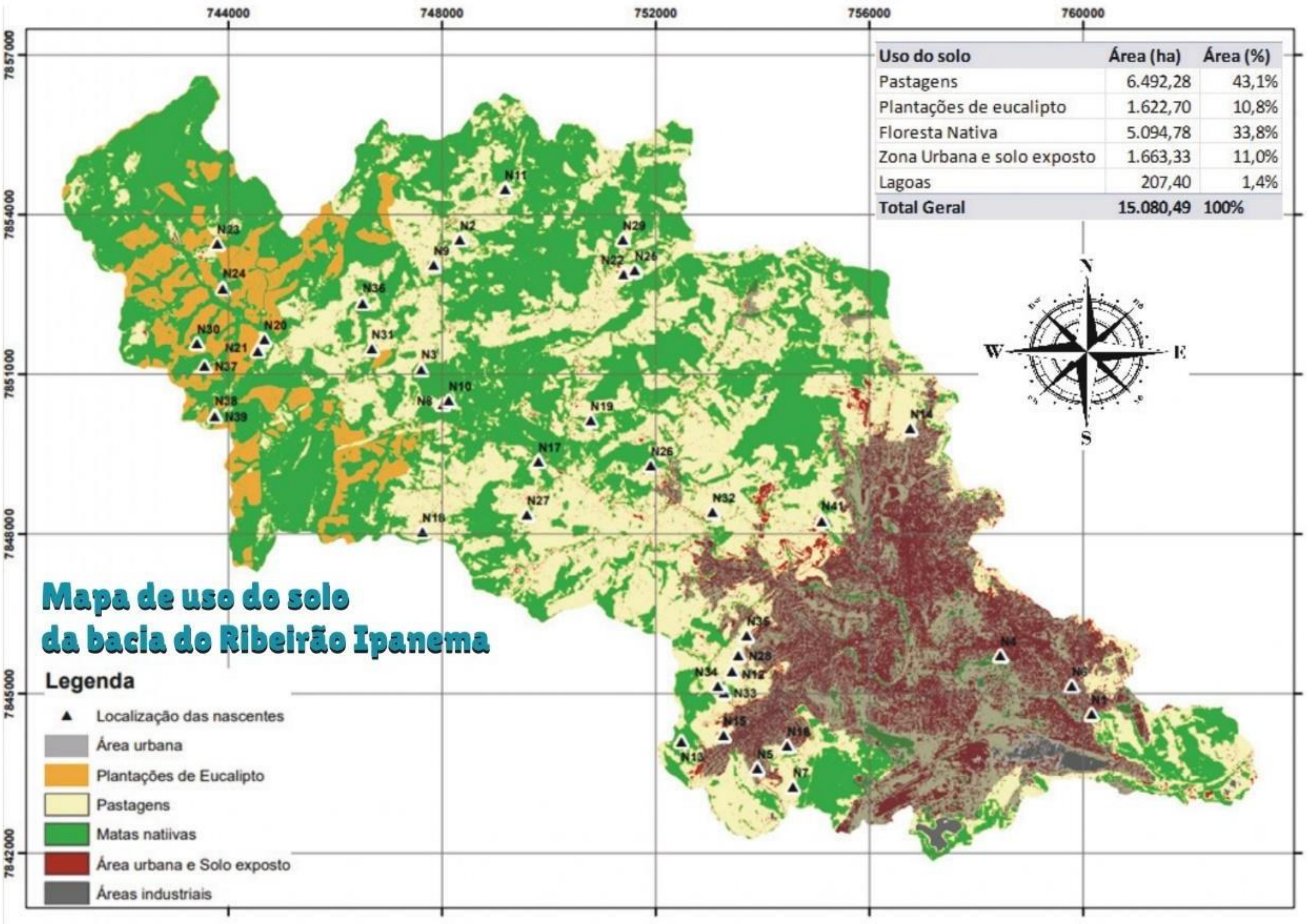
O **ciclo da água** é o permanente processo de transformação da água na natureza, passando de um estado para outro (líquido, sólido ou gasoso). A esse conjunto de transformações e circulação da água pelo planeta dá-se o nome de ciclo da água ou ciclo hidrológico. Por meio dos processos de vaporização, condensação, precipitação, infiltração e transpiração, a água circula na Terra.

Uso, ocupação e degradação do solo

Durante o ciclo da água, a chuva é importante para reabastecer os ecossistemas aquáticos. Toda a vegetação ao redor dos cursos d'água, chamada de mata ciliar, auxilia na retenção da chuva, que se infiltra no solo, recarregando nascentes, lençol freático, rios, lagos, riachos.

Muitas atividades antrópicas, ou seja, atividades realizadas pelo homem, têm causado, nas últimas décadas, a degradação ambiental e a supressão da mata ciliar. O crescimento de áreas urbanas, atividade industrial com lançamento de poluentes atmosféricos e hídricos, aumento das áreas de pastagem e cultivo de eucalipto são os principais impactos que afetam o ecossistema aquático na bacia do Ribeirão Ipanema.





Uso do solo	Área (ha)	Área (%)
Pastagens	6.492,28	43,1%
Plantações de eucalipto	1.622,70	10,8%
Floresta Nativa	5.094,78	33,8%
Zona Urbana e solo exposto	1.663,33	11,0%
Lagoas	207,40	1,4%
Total Geral	**15.080,49**	**100%**

A qualidades da água e os bioindicadores

Para avaliar a saúde de um ecossistema aquático como as nascentes, podemos utilizar algumas ferramentas. A medição de variáveis físicas e químicas de qualidade da água como, temperatura, quantidade de oxigênio dissolvido, pH e condutividade elétrica são alguns parâmetros importantes que podem demonstrar o grau de degradação que o ambiente aquático vem sofrendo.

Diversos seres vivos podem ser selecionados como bioindicadores da qualidade ambiental, e os mais comuns são algas, aves, mamíferos, peixes e macroinvetebrados bentônicos.

Mas o que são bioindicadores?

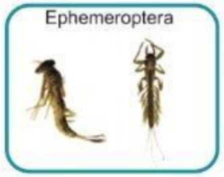
São organismos vivos utilizados para indicar a qualidade de um ambiente. A presença ou ausência de alguns grupos biológicos como algas, aves, mamíferos e peixes, podem ajudar a avaliar se o ambiente está sob impacto ambiental negativo, por isso são chamados de organismos bioindicadores.

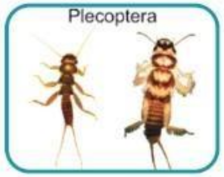
Atualmente muitos trabalhos científicos, além de monitorar as variáveis físico-químicas, utilizam também os macroinvertebrados bentônicos como organismos bioindicadores de qualidade de água.

E os macroinvertebrados betônicos? Quem são esses organismos?

Macro vem do grego que significa “grande”. Na verdade, para o estudo de invertebrados, “grande” pode ser algo com aproximadamente 1cm ou menos. Muitos macroinvertebrados bentônicos têm tamanho aproximado de 5 milímetros, mas podem ser vistos à olho nu.

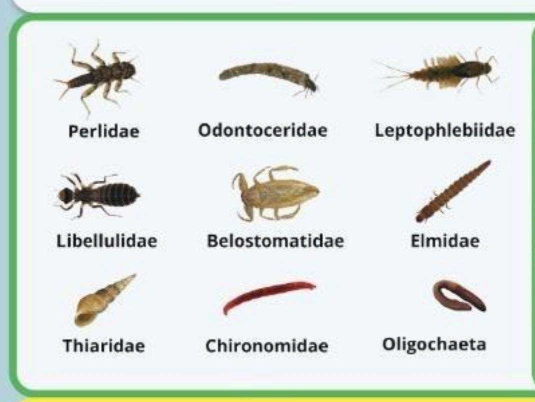
Os macroinvertebrados bentônicos são, em sua maioria, insetos aquáticos ou a larva deles. Esses animais vivem, pelo menos, uma parte do seu ciclo vital na água, mais precisamente enterrados no sedimento, no fundo do leito dos rios, ou seja, enterrados na lama. Por esse motivo, são também chamados de bentônicos, pois “bentos”, é uma palavra de origem grega, benthos = profundidade.





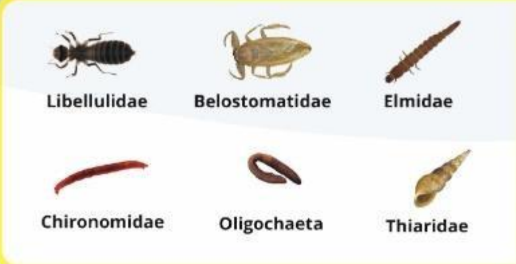
Os grupos de macroinvertebrados betônicos

Os macroinvertebrados bentônicos são divididos em três grupos, de acordo com a sensibilidade à poluição.



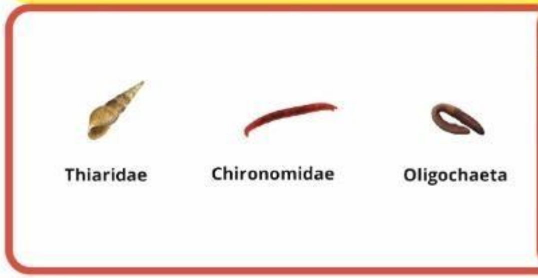
Ecossistemas preservados

Organismos capazes de viver em ambientes com altos níveis de preservação.



Ecossistemas alterados

Organismos capazes de viver em ambientes com certos níveis de degradação.



Ecossistemas impactados

Organismos capazes deviveremambientes com altos níveis de degradação:.

Poluição, impactos ambientais e a comunidade bentônica

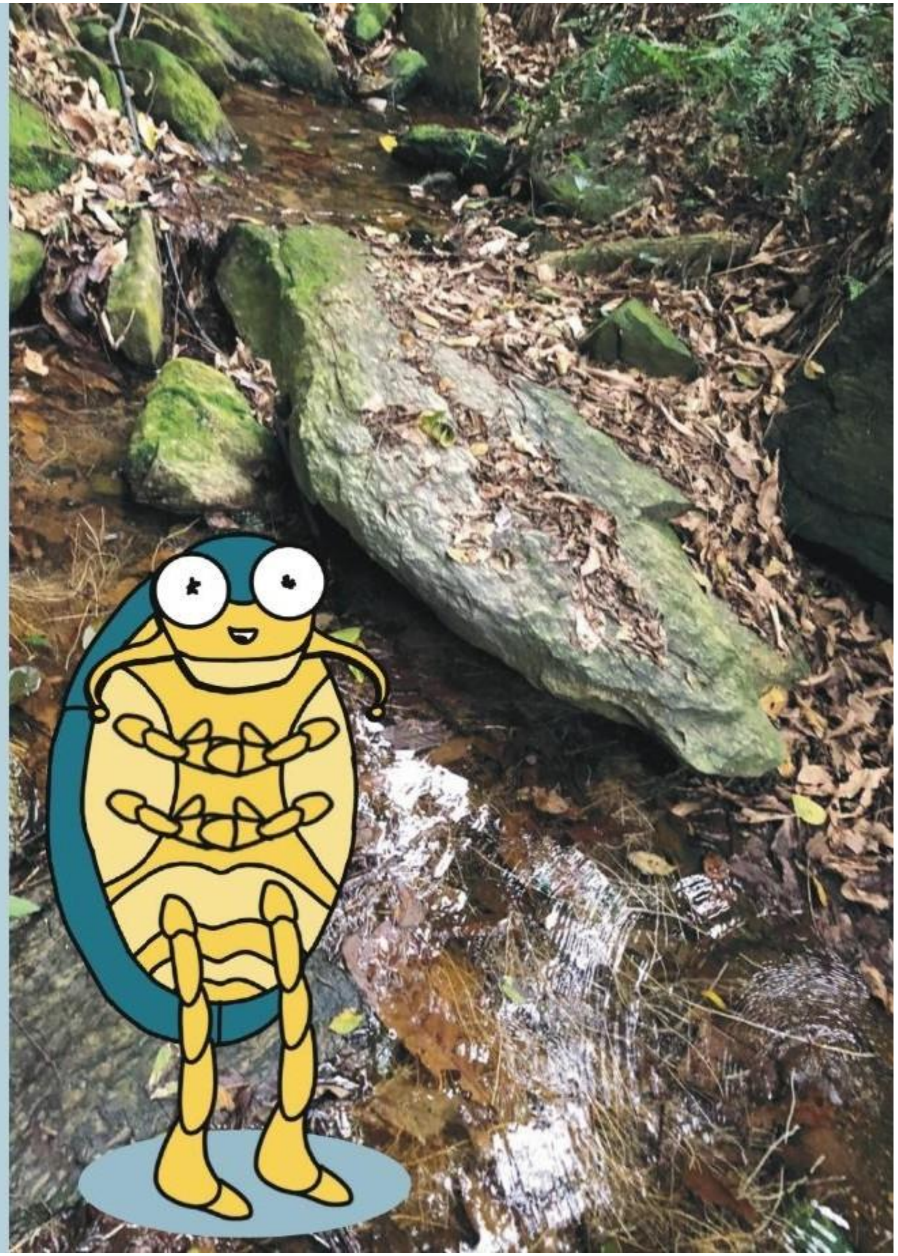
A entrada de poluição proveniente de esgoto, fezes de animais, como bovinos e equinos, fertilizantes de áreas agrícolas, além de desmatamento, podem trazer impactos ambientais negativos para as nascentes e demais corpos d'água.

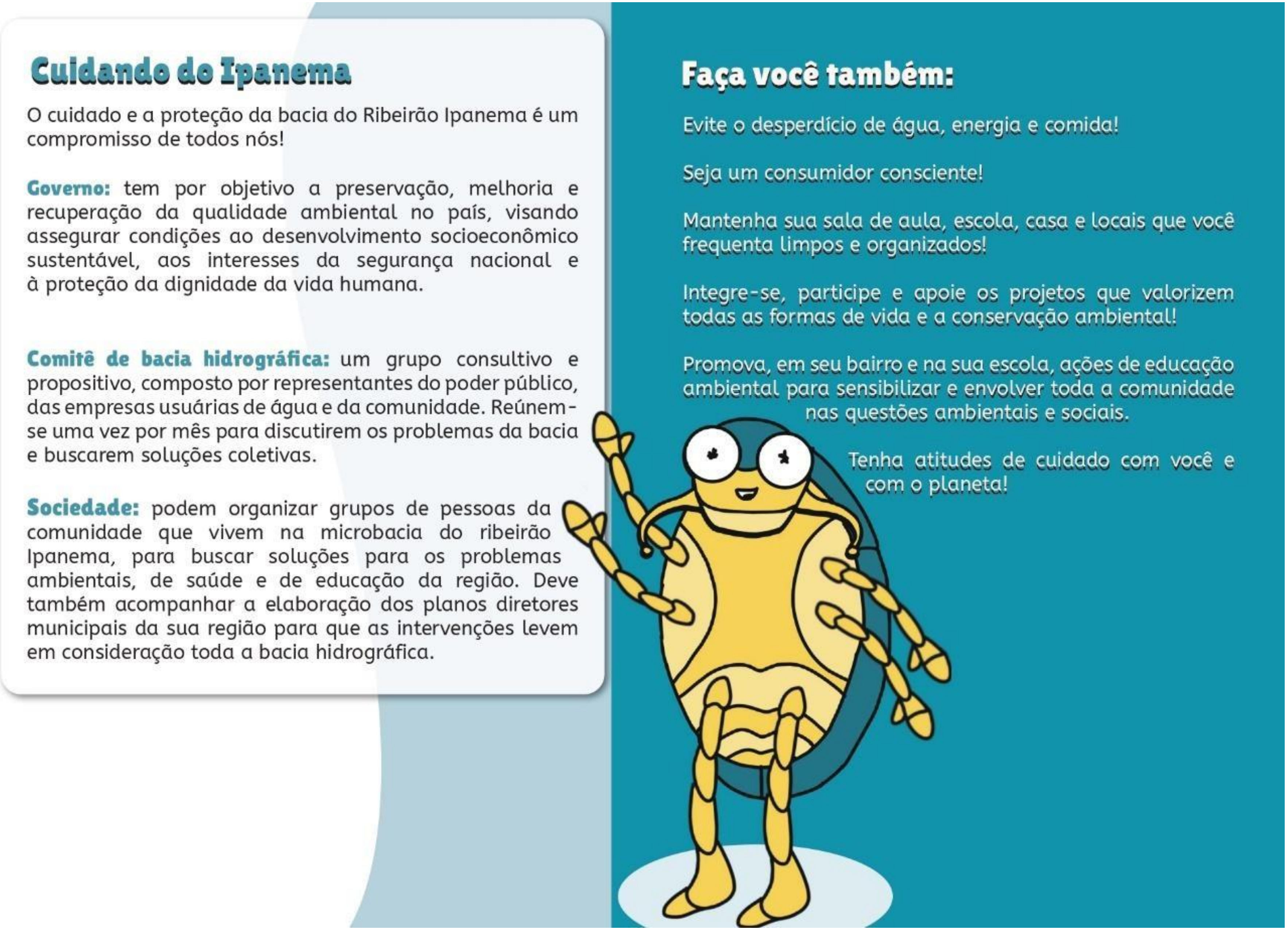
A degradação ambiental afeta a fauna bentônica, além de muitos outros organismos aquáticos, como os peixes. Em ambientes poluídos, apenas os macroinvertebrados bentônicos resistentes à poluição conseguem sobreviver.

Como estes são os únicos organismos presentes, estarão em grande número, ou seja, muitos indivíduos de poucos grupos biológicos, como moluscos, anelídeos e algumas larvas de insetos que suportam ambientes poluídos.

Em ambientes preservados ou com baixo grau de impacto ambiental, é possível encontrar uma maior diversidade de organismos, especialmente aqueles grupos sensíveis à poluição, como Plecoptera, Ephemeroptera e Trichoptera (EPT).

A identificação da fauna bentônica é uma ferramenta importante para avaliação da qualidade da água, pois a presença de alguns grupos biológicos sensíveis à poluição pode indicar bom estado de conservação, enquanto, em ambientes impactados e degradados, apenas organismos resistentes à poluição serão registrados.





Cuidando do Ipanema

O cuidado e a proteção da bacia do Ribeirão Ipanema é um compromisso de todos nós!

Governo: tem por objetivo a preservação, melhoria e recuperação da qualidade ambiental no país, visando assegurar condições ao desenvolvimento socioeconômico sustentável, aos interesses da segurança nacional e à proteção da dignidade da vida humana.

Comitê de bacia hidrográfica: um grupo consultivo e propositivo, composto por representantes do poder público, das empresas usuárias de água e da comunidade. Reúnem-se uma vez por mês para discutirem os problemas da bacia e buscarem soluções coletivas.

Sociedade: podem organizar grupos de pessoas da comunidade que vivem na microbacia do ribeirão Ipanema, para buscar soluções para os problemas ambientais, de saúde e de educação da região. Deve também acompanhar a elaboração dos planos diretores municipais da sua região para que as intervenções levem em consideração toda a bacia hidrográfica.

Faça você também:

Evite o desperdício de água, energia e comida!

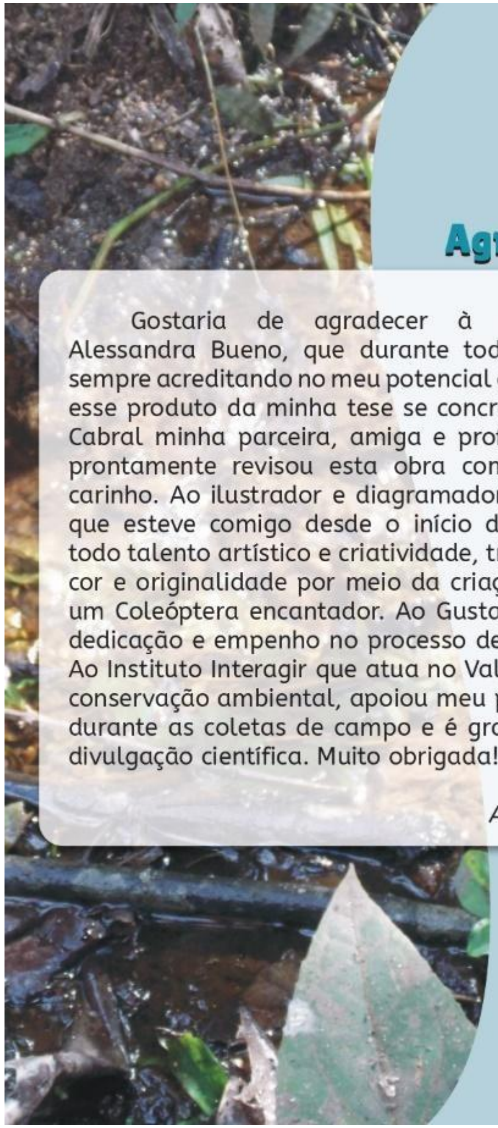
Seja um consumidor consciente!

Mantenha sua sala de aula, escola, casa e locais que você frequenta limpos e organizados!

Integre-se, participe e apoie os projetos que valorizem todas as formas de vida e a conservação ambiental!

Promova, em seu bairro e na sua escola, ações de educação ambiental para sensibilizar e envolver toda a comunidade nas questões ambientais e sociais.

Tenha atitudes de cuidado com você e com o planeta!



Agradecimentos

Gostaria de agradecer à minha orientadora Alessandra Bueno, que durante todo doutorado esteve sempre acreditando no meu potencial e me apoiou para que esse produto da minha tese se concretizasse. A Fernanda Cabral minha parceira, amiga e profissional exímia, que prontamente revisou esta obra com toda dedicação e carinho. Ao ilustrador e diagramador Fernando Hemétrio que esteve comigo desde o início desta produção, com todo talento artístico e criatividade, trazendo mais beleza, cor e originalidade por meio da criação do nosso Avatar, um Coleóptera encantador. Ao Gustavo Bretas Lage pela dedicação e empenho no processo de criação dos mapas. Ao Instituto Interagir que atua no Vale do Aço em prol da conservação ambiental, apoiou meu projeto de doutorado durante as coletas de campo e é grande incentivador da divulgação científica. Muito obrigada!

Alice Arantes Carneiro

CONCLUSÃO GERAL

Nossa tese objetivou fornecer informações sobre como os diferentes usos da terra impactam a comunidade de macroinvertebrados bentônicos em nascentes. Observamos que a remoção da vegetação ciliar no entorno das nascentes afeta a riqueza, diversidade e composição da fauna bentônica. Observamos ainda que, a substituição da vegetação nativa por outros usos da terra como eucalipto, pastagem e áreas urbanas reduzem a diversidade taxonômica e reduz a abundância dos grupos funcionais de alimentação de macroinvertebrados bentônicos. É importante ressaltar que, os habitats de nascentes estão cada vez mais sob pressões antrópicas, fato que compromete a qualidade e quantidade de recursos hídricos, importantes serviços ecossistêmicos para a humanidade. Estudos que avaliem o grau de degradação desses ambientes gerando dados robustos acerca das alterações na biota aquática são fundamentais para que planos de manejo dessas áreas bem como políticas públicas regionais, sejam elaborados com base nos princípios da conservação dos recursos hídricos em prol da sustentabilidade.