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Hydroenvironmental Assessment of Springs and Stream Water Quality in a Mountain Watershed of Southeastern Brazil

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Abstract

Springs are important components of headwater ecosystems, but macroscopic environmental assessments do not necessarily characterize their hydrological conditions. This study evaluated macroscopic environmental conditions and observed surface-flow occurrence at seven springs in the Ribeirão do Caracol watershed, southeastern Brazil, and characterized oxygen-related water quality at three stream stations. Spring surveys were conducted during the rainy (October 2024) and dry (June 2025) seasons. Macroscopic conditions were evaluated using the Environmental Impact Index in Springs (EIIS), while dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) were determined from water samples collected in June 2024 or June 2025. Four springs exhibited observable surface discharge during both surveys, whereas three (S4, S5, and S7) showed no observable discharge on either occasion. Among the four springs with complete EIIS assessments, S6 received the highest score (35 points), followed by S1 (32 points), while S2 and S3 obtained identical scores (27 points) despite contrasting environmental pressures. Water-quality measurements indicated pronounced oxygen depletion and elevated biochemical oxygen demand at ST2 (DO: 1.50 mg L^{-1}; BOD_5: 17.76 mg L^{-1}) and elevated BOD_5 at ST3 (8.48 mg L^{-1}). However, ST2 was sampled in

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June 2024, whereas ST1 and ST3 were sampled in June 2025, preventing interpretation of the measurements as a simultaneous spatial gradient. The findings show that macroscopic classifications identify visible environmental pressures but do not directly characterize discharge magnitude or flow permanence. Integrating macroscopic assessments with surface-flow observations and water-quality measurements provides complementary information for preliminary spring assessment and watershed management.

Keywords
Spring ecosystems; macroscopic environmental assessment; headwaters; surface-flow occurrence; water quality; Atlantic Forest

1. Introduction

Freshwater ecosystems are increasingly affected by land-use changes, urban expansion, and agricultural activities, with consequences for water availability, water quality, and aquatic biodiversity [1-4]. These pressures reinforce the importance of integrated watershed management, particularly where human activities interact with hydrologically sensitive environments. Watersheds integrate physical and ecological processes that regulate freshwater flow, storage, and quality [5-7]. Inadequate land-use planning can alter these processes by intensifying soil erosion, surface runoff, and contaminant transport [8-11]. Consequently, increasing attention has been directed toward headwater ecosystems, whose hydrological connectivity and ecological functions influence downstream water resources [11-15]. Their conservation also aligns with the United Nations 2030 Agenda for Sustainable Development, particularly SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land), which emphasize the protection of water-related ecosystems and sustainable terrestrial ecosystem management.

Springs are essential components of headwater systems, representing locations where groundwater emerges at the land surface and contributing to the connection between subsurface and surface-water environments. Their hydrological characteristics depend on groundwater dynamics, geological conditions, and subsurface flow pathways, which influence discharge occurrence and variability [16, 17]. Springs also provide habitats for specialized aquatic and semi-aquatic organisms, including species adapted to particular physicochemical and hydrological conditions, contributing to freshwater biodiversity [18-21]. Beyond their ecological importance, springs contribute to water availability for human activities, particularly in rural and mountainous regions. However, their environmental conditions may be affected by vegetation removal, sedimentation, pollution, water abstraction, and changes in surrounding land use [21-23]. These pressures have reinforced calls for improved protection and monitoring of spring ecosystems [24].

In Brazil, the protection of springs is addressed by federal legislation, particularly Law No. 12.651/2012 [25], which establishes provisions for Permanent Preservation Areas (Áreas de Preservação Permanente, APPs). Nevertheless, the conservation and monitoring of these environments remain challenging, especially where agricultural activities, infrastructure development, and urban occupation coexist. Similar challenges have been recognized in broader discussions of mountain ecosystems, water-resource governance, and freshwater conservation [26-

29]. The importance of integrating land management and hydrological processes has also been emphasized in studies addressing the role of forests and mountainous regions in water-resource sustainability [30, 31]. In this context, environmental assessments can provide information for identifying local pressures and supporting conservation priorities, particularly where long-term hydrological monitoring is limited. Macroscopic assessment protocols have been widely applied to characterize the environmental conditions of springs through observable indicators such as water appearance, waste accumulation, vegetation condition, human and animal activity, and proximity to built structures. In Brazil, some studies have demonstrated the applicability of these approaches for documenting environmental pressures and supporting spring management [32-35]. However, macroscopic indicators do not necessarily represent all dimensions of spring functioning. In particular, discharge magnitude and flow permanence depend on groundwater storage, hydrogeological characteristics, and subsurface connectivity, which may not be reflected in visual assessments of the spring surroundings [16, 17]. Likewise, visually favorable water characteristics do not necessarily indicate the absence of dissolved or microbiological contamination. Although macroscopic evaluations provide useful information on local environmental conditions, their interpretation alongside hydrological observations and direct water-quality measurements requires distinguishing the processes represented by each assessment.

This distinction is particularly relevant in mountainous watersheds where springs occur across landscapes with contrasting land uses and contribute to local water resources. The Ribeirão do Caracol watershed, located in Andradas, southern Minas Gerais, Brazil, lies within the Atlantic Forest biome and includes springs associated with native vegetation fragments, agricultural areas, and urban environments. The watershed is also relevant to municipal water-supply management. Previous studies have demonstrated the usefulness of macroscopic indices for assessing spring surroundings [34, 35], but the interpretation of their classifications alongside observations of surface-flow occurrence and stream water quality remains relevant, particularly where hydrological information is limited. Examining these dimensions can help identify environmental pressures while clarifying the extent to which different field indicators provide complementary, rather than equivalent, information about spring conditions. Therefore, this study aimed to characterize the macroscopic environmental conditions and observed surface-flow occurrence of selected springs in the Ribeirão do Caracol watershed and to provide a complementary assessment of stream water quality based on dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) measurements. Specifically, the study sought to identify differences in visible environmental pressures among springs, examine the interpretation of macroscopic environmental classifications in relation to observed flow conditions, and describe oxygen-related water-quality conditions at selected stream locations.

2. Materials and Methods

2.1 Study Area

The municipality of Andradas (22°04’05” S, 46°34’04” W) is located in southern Minas Gerais, southeastern Brazil, approximately 485 km from the state capital, Belo Horizonte. It encompasses a total area of 469.396 km^2 and has a population of 40,553 inhabitants. The urbanized area covers 8.77 km^2, and the municipal seat is located at an elevation of 920 meters above sea level [36]. Andradas lies within the Atlantic Forest biome and includes ecotonal zones with the Cerrado. Its

vegetation cover comprises Semideciduous Seasonal Forest and high-altitude grasslands. The topography is diverse, including northern plateaus (1,350-1,500 m), central rolling hills (900-970 m), and mountainous areas such as Pico do Gavião, which reaches 1,657 meters in elevation [37].

The region features a high-altitude tropical climate (Cwb), characterized by warm, humid summers and dry winters [38], which favors viticulture and other agricultural activities. The mean annual precipitation is approximately 1,468 mm, with the highest rainfall occurring between October and March and and a dry period from May to August (Figure 1). The average minimum temperature is 16.3°C, while the average maximum temperature reaches 26.7°C [39]. The municipal water supply originates from the Serra do Caracol, a region with a dendritic drainage network and several waterfalls. It supports six micro-watersheds, including the Jaguari-Mirim River, Ribeirão das Antas, and Ribeirão do Caracol. These watercourses collectively supply potable water to 77.69% of the population through the municipal distribution system [40].

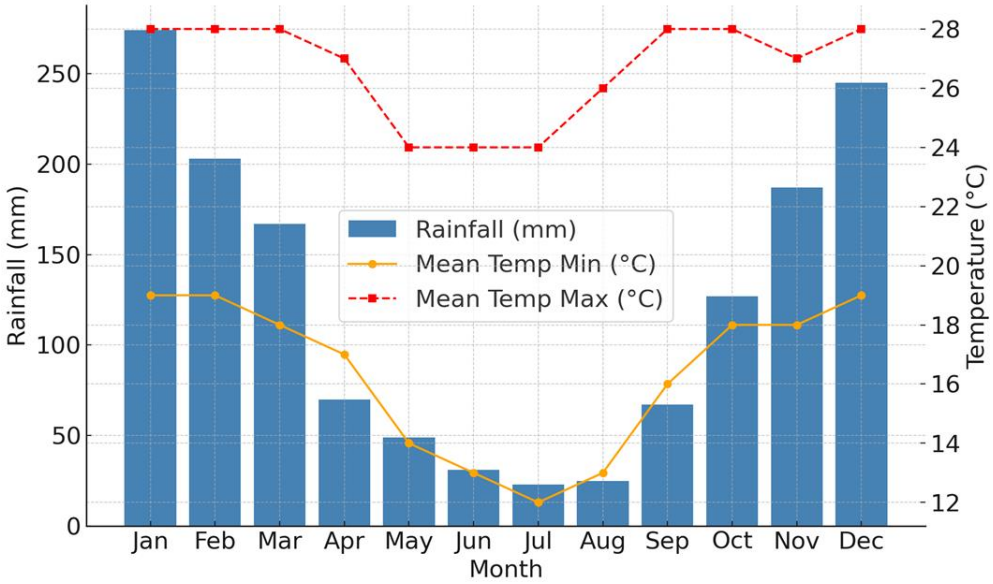


Figure 1 Monthly rainfall (bars) and mean air temperatures (lines) in Andradas, southeastern Brazil. Data represent the average monthly values of precipitation (mm) and minimum/maximum air temperature (°C). Source: Meteoblue (2025) [39].

Given its ecological significance and hydrological importance, the Ribeirão do Caracol watershed—entirely located within the municipality - was selected as the study area. Covering 13.63 km^2, the watershed is representative of local environmental dynamics and socio-environmental challenges, including inadequate sewage disposal and insufficient waste segregation. These issues have mobilized local civil society organizations such as Impressão Verde and the NGO Caracol, which actively promote environmental conservation and reforestation efforts [40].

2.2 Methodological Procedures

Spring mapping was based on spatial data provided by the Institute of Geosciences and Cartography (IGC) and the State Secretariat for the Environment. These data were processed using QGIS software (version 3.32.2) to identify spring locations and guide field surveys (Figure 2). A total of 35 springs were identified within the Ribeirão do Caracol watershed, of which seven (20%) were

investigated in the field. Spring selection considered spatial distribution and accessibility, with restrictions on access to private properties limiting the number of locations that could be assessed. Of the seven investigated springs, six were located in rural areas (S1, S2, S4, S5, S6, and S7), while S3 was situated in an urban setting. Field surveys were conducted on October 14, 2024 (rainy season), and June 16, 2025 (dry season), to characterize observable spring conditions and surface-flow occurrence. No rainfall was recorded during the five days preceding either survey (October 9-13, 2024, and June 11-15, 2025). Surface-flow occurrence was recorded during both field surveys. Discharge was generally too low for reliable quantification using the available field procedure. A quantitative flow measurement was obtained only at S1 using the float method, while flow conditions at the remaining springs were documented qualitatively as observable low flow or no observable surface discharge. Spring emergence characteristics were also assessed in the field and classified as point springs, when water emerged at a single identifiable location, or diffuse springs, when water emerged at multiple locations within the spring area [25, 34]. Given the limited number of observations, the surveys were not used to establish definitive perennial, intermittent, or ephemeral flow regimes.

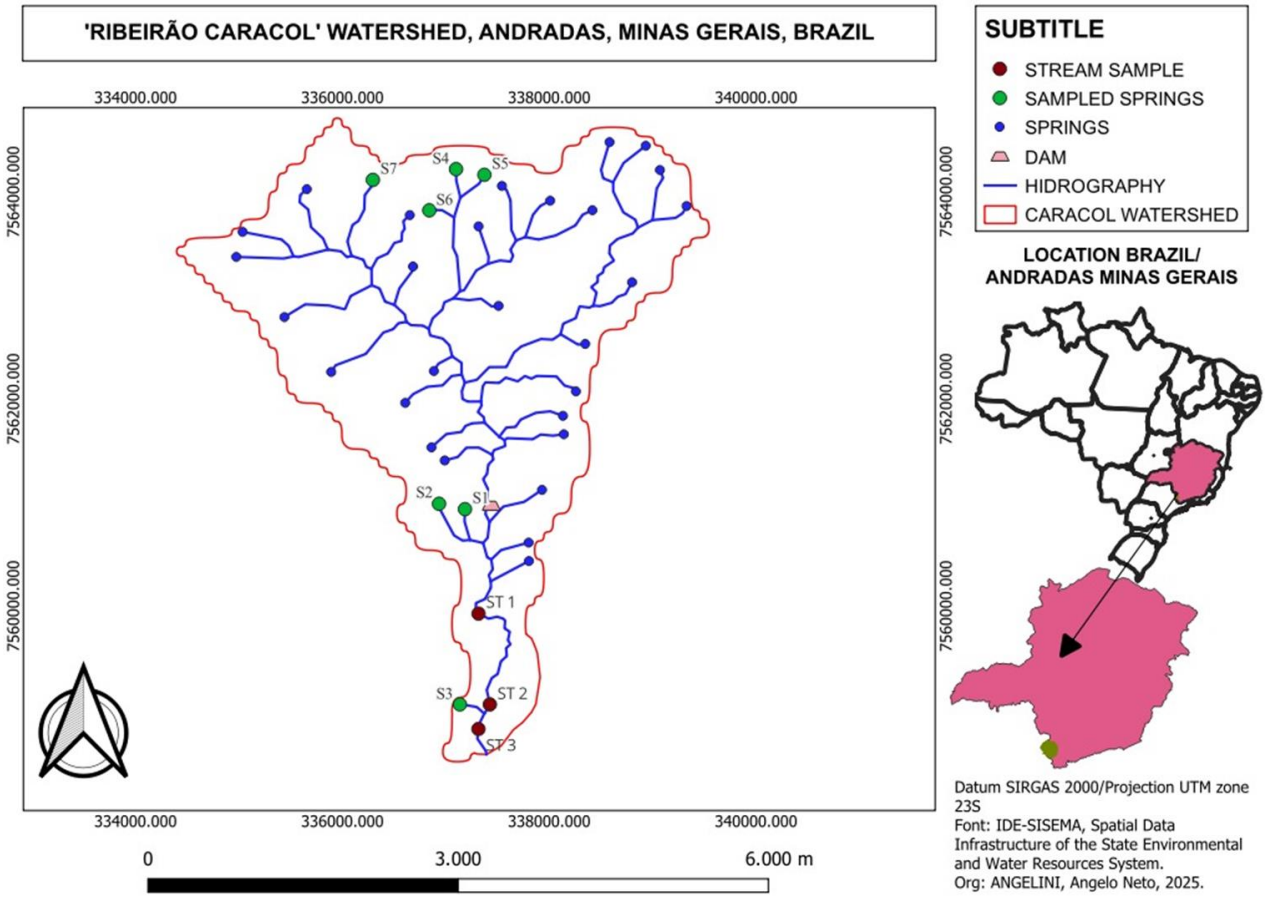


Figure 2 Location of the Ribeirão do Caracol watershed in Andradas, Minas Gerais, southeastern Brazil, showing the 35 mapped springs, including the seven springs assessed in the field (S1-S7), and the three stream water-quality sampling stations (ST1-ST3). Source: IDE-SISEMA spatial data; map prepared using QGIS 3.32.2.

Macroscopic environmental assessments were conducted using field evaluation forms adapted from established spring assessment protocols [32-35]. The assessments considered twelve

observable indicators related to water appearance, solid waste, floating materials, foam, oil, sewage-related evidence, vegetation condition, human and animal activity, site protection, and proximity to built structures. The indicators and their respective scoring criteria are presented in Table 1. Complete macroscopic assessments were available for four springs (S1, S2, S3, and S6) during the October 2024 survey. Springs S4, S5, and S7 could not be fully evaluated because the absence of observable surface water prevented assessment of the water-related indicators.

Table 1 Macroscopic indicators and scoring criteria used to assess the environmental conditions of springs in the Ribeirão do Caracol watershed.

Macroscopic indicator	Score 1	Score 2	Score 3
Water color	Milky	Turbid	Transparent
Water odor	Strong, unpleasant odor	Slight odor	No perceptible odor
Solid waste in the protected area	Abundant	Small amount	Absent
Floating materials	Abundant	Few	Absent
Foam	Abundant	Small amount	Absent
Oil	Abundant	Small amount	Absent
Sewage-related evidence	Visible domestic sewage discharge	Surface flow of sewage	No visible sewage discharge
Vegetation condition	Vegetation removed	Early successional stage	Intermediate successional stage
Human activity	Visible activity	Traces of activity	No activity detected
Animal presence	Domestic animals or livestock observed	Traces of animal presence	No domestic animals or livestock detected
Site protection	No protection	Protected but accessible	Protected with restricted access
Proximity to residential or other built structures	<50 m	50-100 m	>100 m

Note: Scores range from 1 (least favorable environmental condition) to 3 (most favorable environmental condition). The total score ranges from 12 to 36, with higher values indicating more favorable macroscopic conditions. Surface-flow occurrence and discharge magnitude are not included in the scoring system.

Stream water quality was assessed independently of the spring macroscopic evaluations, using dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) measurements at three sampling stations along the Ribeirão do Caracol watercourse (Figure 2). ST1 was located in the upstream rural section, ST2 downstream of areas influenced by rural and urban land uses, and ST3 near the watershed outlet. Sampling was conducted in June 2024 at ST2 and in June 2025 at ST1 and ST3. At each station, multiple aliquots collected at the same location and sampling time were combined into a single pooled sample for laboratory analysis. Therefore, each station was represented by one sampling event, without independent spatial or temporal replication. Water sampling procedures followed ABNT NBR 9898:1987 with analytical procedures referenced to the 24th edition of Standard Methods for the Examination of Water and Wastewater [41]. Expanded

measurement uncertainty was calculated following the Brazilian Guide to the Expression of Uncertainty in Measurement, using a coverage factor of k = 2.0 and an approximate confidence level of 95%. The measurements were interpreted as individual sampling-event observations rather than as estimates of seasonal or annual water-quality conditions.

2.3 Data Analyses

The macroscopic environmental conditions of the springs were assessed using the Environmental Impact Index in Springs (EIIS), following the approach [32, 35], based on established macroscopic assessment protocols. Twelve indicators were considered, encompassing observable water characteristics, waste and sewage occurrence, vegetation condition, human and animal activity, site protection, and proximity to built structures (Table 1). Each indicator was assigned a score ranging from 1 (least favorable condition) to 3 (most favorable condition). Total scores therefore ranged theoretically from 12 to 36, with higher values indicating more favorable macroscopic environmental conditions.

The EIIS was calculated for four springs (S1, S2, S3, and S6), for which all twelve indicators could be evaluated. Springs S4, S5, and S7 were excluded from the index because the absence of observable surface water prevented the assessment of water-related indicators. Their surface-flow conditions were described separately. An adapted classification procedure based on the approach described by Souza et al. [35] was used to group the total EIIS scores into five environmental quality categories (A-E). Category boundaries were calculated using the arithmetic mean and sample standard deviation of the four evaluated springs, with thresholds defined at the mean plus one standard deviation, the mean, the mean minus one standard deviation, and the mean minus two standard deviations (Table 2). The resulting mean was 30.25, and the sample standard deviation was approximately 3.95. Because these boundaries were derived from only four springs, the categories were interpreted as descriptive and sample-dependent rather than externally validated thresholds of environmental integrity. Surface-flow occurrence was assessed independently of the EIIS using field observations from October 2024 and June 2025. Because discharge magnitude and flow permanence are not included among the EIIS indicators, the environmental classifications were not interpreted as measures of hydrological functioning. Furthermore, the two observation periods were insufficient to establish definitive perennial, intermittent, or ephemeral flow regimes.

Table 2 Relative classification of macroscopic environmental conditions based on the Environmental Impact Index in Springs (EIIS).

Category	Score Range	Description
A - Excellent	≥34.20	Excellent macroscopic condition
B - Good	From 30.25 to <34.20	Good macroscopic condition
C - Fair	From 26.30 to <30.25	Moderate macroscopic condition
D - Poor	From 22.35 to <26.30	Poor macroscopic condition
E - Very poor	<22.35	Very poor macroscopic condition

Note. Classification thresholds were calculated from the four spring scores (S1 = 32, S2 = 27, S3 = 27, and S6 = 35), using the arithmetic mean (30.25) and sample standard deviation (3.95). The resulting categories are relative to this sample and do not constitute externally validated environmental quality standards.

3. Results and Discussion

3.1 Macroscopic Environmental Conditions and Observed Spring Flow

Seven springs were investigated in the Ribeirão do Caracol watershed during the rainy (October 2024) and dry (June 2025) seasons (Table 3). Differences in surface-flow occurrence and macroscopic environmental conditions were observed among the surveyed locations. Springs S1, S2, S3, and S6 exhibited observable surface flow during both field campaigns, whereas S4, S5, and S7 showed no observable surface discharge during either survey. These observations document spatial differences in spring conditions, although the two campaigns were insufficient to establish definitive flow-permanence regimes.

Table 3 Observed surface-flow occurrence and macroscopic characteristics of seven springs in the Ribeirão do Caracol watershed, southeastern Brazil.

Spring	Surface flow, 14 Oct 2024	Surface flow, Jun 2025	Emergence type	Main environmental characteristics
S1	Low flow	Low flow	Point	Intermediate-stage vegetation; turbid water; concrete structures and pipes
S2	Low flow	Low flow	Diffuse	Vegetation removal; livestock access; small amounts of solid waste
S3	Low flow	Low flow	Point	Urban setting; human activity; domestic animals; solid waste; nearby buildings
S4	No surface discharge observed	No surface discharge observed	Not determined	Intermediate-stage vegetation
S5	No surface discharge observed	No surface discharge observed	Not determined	Intermediate-stage vegetation
S6	Low flow	Low flow	Point	Intermediate-stage vegetation; transparent water; no visible waste or sewage discharge
S7	No surface discharge observed	No surface discharge observed	Not determined	Intermediate-stage vegetation

Notes. Surface-flow conditions represent qualitative field observations during the two surveys and do not establish perennial, intermittent, or ephemeral flow regimes. Water-related macroscopic indicators could not be assessed at S4, S5, and S7 because no observable surface water was present.

Springs S4, S5, and S7, located in the upper portion of the watershed, exhibited no observable surface discharge during either assessment, despite the presence of surrounding native vegetation. Spring discharge depends on local hydrogeological conditions, groundwater dynamics, and

subsurface flow pathways [17]. Therefore, the absence of surface discharge during two field observations does not necessarily indicate permanent spring cessation or a decline in groundwater recharge. Although roads, agricultural greenhouses, and water-use infrastructure were identified in the surrounding landscape, their influence on spring discharge could not be determined from the available data. Establishing such relationships would require additional hydrological monitoring and characterization of subsurface conditions. The absence of observable water also prevented the application of the complete Environmental Impact Index in Springs (EIIS) to S4, S5, and S7 because several water-related indicators could not be evaluated. Similar methodological constraints were reported by Souza et al. [35], who excluded springs without observable water characteristics from macroscopic index calculations. Spring S6 exhibited low surface flow during both campaigns. Its macroscopic assessment indicated transparent water, absence of visible waste, foam, oil, and sewage-related evidence, intermediate-stage vegetation, and no detected human activity. Accordingly, S6 received the highest EIIS score (35 points), corresponding to category A - Excellent (Table 4). This classification describes favorable observable environmental conditions but does not establish discharge magnitude or flow permanence. The distinction reflects the scope of macroscopic indices, which characterize environmental attributes of spring surroundings without directly measuring the hydrological processes controlling discharge [17, 35].

Table 4 Individual macroscopic indicator scores, total EIIS scores, and environmental quality classifications for the four assessed springs in the Ribeirão do Caracol watershed.

Macroscopic indicator	S1	S2	S3	S6
Water color	2	3	3	3
Water odor	3	3	3	3
Solid waste	3	2	2	3
Floating materials	3	3	3	3
Foam	3	3	3	3
Oil	3	3	3	3
Sewage-related evidence	3	3	3	3
Vegetation condition	3	1	3	3
Human activity	2	1	1	3
Animal presence	3	1	1	3
Site protection	1	1	1	2
Proximity to built structures	3	3	1	3
Total EIIS score	32	27	27	35
Environmental class	B	C	C	A

Note. Scores range from 1 (least favorable) to 3 (most favorable). Higher totals indicate more favorable macroscopic conditions. The EIIS does not include discharge magnitude or flow permanence. Environmental classes: A, Excellent; B, Good; C, Fair.

Spring S1 also exhibited surface flow during both field campaigns and presented relatively favorable macroscopic conditions, including intermediate-stage vegetation, absence of solid waste, and no visible sewage-related evidence. However, turbid water and traces of human activity were recorded. Its EIIS score was 32 points, corresponding to category B - Good (Table 4). Vegetation

surrounding springs can contribute to soil protection and sediment retention, although the effectiveness of these functions depends on vegetation structure, soil properties, and local hydrological conditions [34, 42]. As these processes were not directly quantified, the observed characteristics indicate comparatively limited macroscopic disturbance at S1 rather than demonstrated effects on infiltration or water quality. Spring S2, characterized by diffuse groundwater emergence, exhibited low surface flow and several signs of anthropogenic disturbance, including vegetation removal, small amounts of solid waste, and visible human and livestock activity. It received an EIIS score of 27 points and was classified as category C - Fair. Livestock access and vegetation removal may affect near-surface hydrological conditions through soil disturbance, trampling, and compaction [43]. However, soil physical properties and infiltration were not measured in this study, preventing direct attribution of these processes to the conditions observed at S2. The macroscopic assessment therefore documents environmental pressures that warrant further investigation rather than quantifying their hydrological consequences. Spring S3, the only spring situated in an urban area, also exhibited low surface flow. Its surroundings were characterized by solid waste, visible human activity, domestic animals, absence of site protection, and proximity to built structures within 50 m. Despite these disturbances, transparent water, absence of perceptible odor, and intermediate-stage vegetation were recorded. S3 received an EIIS score of 27 points, corresponding to category C - Fair. Comparable environmental pressures have been documented in urban spring environments, particularly those associated with waste disposal, human accessibility, and surrounding infrastructure [35]. Nevertheless, visually favorable water characteristics do not establish microbiological safety or the absence of dissolved contaminants. Although S2 and S3 received identical EIIS scores, their individual indicator profiles differed (Table 4). S2 was characterized by vegetation removal and livestock presence, whereas S3 presented greater proximity to built structures and evidence of human activity. Similar aggregate EIIS scores may therefore reflect different combinations of environmental pressures. EIIS scores ranged from 27 to 35 points among the four classified springs. Because the index does not incorporate discharge magnitude, flow permanence, or microbiological indicators, these scores cannot independently characterize the overall hydroecological functioning of the investigated springs.

3.2 Stream Water Quality and Implications for Watershed Management

Dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) measurements indicated differences in oxygen-related water-quality conditions among the three stream sampling stations (Table 5). However, the samples were collected in different years: ST2 was sampled in June 2024, whereas ST1 and ST3 were sampled in June 2025. Each station was represented by a single pooled sample collected during one sampling event. Consequently, these measurements describe conditions at the respective locations and sampling times and cannot be interpreted as a simultaneous spatial gradient of water-quality degradation. At ST1, located in the upstream rural section of the watercourse and associated with the municipal water-supply intake, DO was 7.10 mg L^{-1}, while BOD_5 was below 2.00 mg L^{-1}. These measurements indicate relatively favorable oxygen conditions and low detectable biochemical oxygen demand at the time of sampling. Vegetated riparian areas may contribute to stream-water protection by influencing sediment and pollutant transport, although their effectiveness depends on local hydrological connectivity and surrounding

land use [42, 44]. However, the present measurements do not allow the contribution of riparian vegetation to the observed water-quality conditions to be quantified.

Table 5 Dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) concentrations in pooled water samples collected at three stream stations in the Ribeirão do Caracol watershed, southeastern Brazil.

ID	Date	DO (mg L^{-1})	BOD_5 (mg L^{-1})
ST 1	Jun-2025	7.10	<2.00
ST 2	Jun-2024	1.50	17.76
ST 3	Jun-2025	5.10	8.48

Note: Each result corresponds to one pooled sample prepared from aliquots collected at the same location and sampling time. ST2 was sampled in June 2024, whereas ST1 and ST3 were sampled in June 2025. Therefore, the results do not represent simultaneous spatial sampling. The reported BOD_5 value below 2.00 mg L^{-1} was retained as provided by the laboratory.

The ST2 sample, collected in June 2024, exhibited the lowest DO concentration (1.50 mg L^{-1}) and the highest BOD_5 concentration (17.76 mg L^{-1}). These values indicate pronounced oxygen depletion and elevated biochemical oxygen demand during that sampling event. Such conditions are consistent with processes associated with organic matter decomposition and microbial oxygen consumption in aquatic environments. Nevertheless, the available data do not establish the sources responsible for the observed conditions. Although ST2 is located downstream of areas subject to rural and urban influences, contributions from sewage discharge, surface runoff, or other organic matter inputs cannot be distinguished using DO and BOD_5 measurements alone. At ST3, sampled in June 2025 near the watershed outlet, DO was 5.10 mg L^{-1} and BOD_5 was 8.48 mg L^{-1}. The elevated BOD_5 concentration indicates appreciable biochemical oxygen demand, despite the DO concentration being above the minimum reference value for Class II freshwater bodies. According to CONAMA Resolution No. 357/2005 and COPAM-CERH/MG Normative Deliberation No. 8/2022, the reference values for Class II freshwaters are a minimum DO concentration of 5 mg L^{-1} and a maximum BOD_5 concentration of 5 mg L^{-1}. When considered against these reference values, ST1 satisfied both criteria, ST2 fell outside both criteria, and ST3 exceeded the BOD_5 reference value while satisfying the DO criterion. These comparisons are conditional on the applicable water-body classification and refer only to the individual sampling events; they do not constitute formal water-body classification or establish persistent regulatory noncompliance.

The observed differences are environmentally relevant because oxygen availability and biochemical oxygen demand are associated with organic matter processing and aquatic habitat conditions. However, DO concentrations are influenced by several interacting factors, including water temperature, streamflow, reaeration, biological activity, and organic matter inputs. As these variables were not monitored concurrently, the mechanisms responsible for the observed concentrations cannot be established. Furthermore, the temporal difference between the ST2 and ST1/ST3 sampling events prevents direct comparison of the measurements as a downstream progression. Water abstraction for municipal supply represents an additional consideration for watershed management, particularly because streamflow influences aquatic habitat availability and the dilution and transport of dissolved and particulate substances. Nevertheless, stream discharge

at the sampling stations, abstraction volumes, and the Q7,10 reference flow were not quantified in this study. Therefore, the available data cannot determine whether water withdrawals influenced downstream oxygen conditions or whether minimum residual-flow requirements were satisfied. Such assessments would require concurrent measurements of streamflow, water quality, and abstraction rates. Despite their limited spatial and temporal coverage, the observations identify locations where additional water-quality investigation is warranted, particularly ST2 and ST3.

3.3 Integrating Spring Assessments and Stream Water Quality for Watershed Management

The combined assessment of springs and stream water quality in the Ribeirão do Caracol watershed provided complementary information on local environmental conditions. Macroscopic indicators documented differences in vegetation cover, human activity, livestock access, and site protection, while field observations characterized surface-flow occurrence during two contrasting seasonal periods. Stream water-quality measurements provided additional information on oxygen-related conditions at selected locations. However, the different spatial and temporal coverage of these assessments prevents direct attribution of stream water-quality conditions to the environmental status or discharge characteristics of individual springs. The findings also highlight limitations in interpreting spring environmental classifications as indicators of hydrological functioning. Although S6 received the highest EIIS score, this classification reflects favorable macroscopic conditions rather than discharge magnitude or flow permanence. Similarly, the absence of observable surface discharge at S4, S5, and S7 during both surveys could not be attributed to specific environmental pressures. Spring discharge depends on groundwater availability, hydrogeological characteristics, and subsurface flow pathways [17]. Although roads, agricultural infrastructure, and other land-use features were identified in the surrounding landscape, their effects on infiltration, groundwater recharge, or spring discharge were not directly evaluated. Distinguishing natural hydrological variability from anthropogenic influences requires longer discharge records and complementary information on groundwater dynamics [13]. The contrasting environmental pressures identified at S2 and S3 further illustrate the importance of examining individual macroscopic indicators rather than relying exclusively on aggregate EIIS scores. Despite receiving identical classifications, the two springs differed in vegetation condition, livestock presence, and proximity to built structures. Macroscopic assessment protocols can support the identification of visible pressures and the prioritization of local management actions [35].

From a watershed-management perspective, the findings suggest several monitoring priorities. Repeated observations of spring discharge across hydrological seasons would help characterize flow variability and clarify the status of locations without observable surface discharge. Additional assessments of livestock access, vegetation condition, and site protection could support the identification of locally appropriate conservation measures. At the stream sampling stations, repeated physicochemical and microbiological analyses, conducted concurrently with discharge measurements, would help establish whether the unfavorable oxygen-related conditions observed at ST2 and ST3 persist and whether they are associated with specific environmental pressures. Information on water-abstraction volumes would also be necessary to investigate potential interactions between water use and downstream hydrological conditions. Such an integrated approach is consistent with the need to recognize the ecological diversity and hydrogeological sensitivity of spring ecosystems in conservation planning [24]. Several limitations should be

considered when interpreting the findings. The assessment included seven accessible springs, with private-property restrictions constraining site selection, and complete EIIS scores were available for only four locations. The resulting environmental classes were therefore sample-dependent and should not be generalized as absolute indicators of spring integrity. The two field campaigns were insufficient to characterize long-term flow permanence or groundwater-recharge dynamics. Furthermore, stream water quality was represented by one pooled sample per station, with ST2 sampled in a different year from ST1 and ST3. The absence of concurrent streamflow, groundwater-level, abstraction-volume, and broader water-quality measurements also limited the investigation of underlying processes. These limitations restrict statistical generalization and prevent causal attribution of the observed conditions to specific land-use practices or hydrological processes.

4. Conclusions

The assessment of seven springs in the Ribeirão do Caracol watershed identified differences in macroscopic environmental conditions, particularly in vegetation cover, human and animal activity, solid waste, and site protection. Among the four springs evaluated using the Environmental Impact Index in Springs (EIIS), S6 presented the highest score (35 points), followed by S1 (32 points), whereas S2 and S3 received identical scores (27 points) despite exhibiting different combinations of environmental pressures. Regarding surface-flow occurrence, S1, S2, S3, and S6 exhibited observable discharge during both surveys, while S4, S5, and S7 showed no observable surface discharge. These observations indicate that macroscopic classifications describe visible environmental conditions but do not provide direct information on discharge magnitude or establish flow permanence. Stream water-quality measurements identified low dissolved oxygen and elevated biochemical oxygen demand at ST2, as well as elevated biochemical oxygen demand at ST3. However, differences in sampling years and the absence of temporal replication prevented the characterization of consistent spatial or seasonal water-quality patterns. Macroscopic assessments, surface-flow observations, and water-quality measurements characterized distinct aspects of the investigated spring and stream environments.

Author Contributions

Methodology, A.A.N. and K.C.T.; formal analysis, A.A.N., K.C.T., and E.O.N.; investigation, A.A.N.; writing - original draft, A.A.N.; writing - review and editing, A.A.N., K.C.T., and E.O.N. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, OpenAI's ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the authors. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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