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Research Article

Keywords: Streamflow, catchment management, ecohydrology, physicochemical parameters

Posted Date: September 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10436676/v1>

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Hydrological monitoring of springs in a bauxite mining area in the pre-mining situation in the Minas Gerais Forest zone

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Abstract

Effective water resource management is essential to meet demand and resolve conflicting uses. In Brazil, where the economy relies heavily on mineral reserves, bauxite exploration requires rigorous monitoring of hydrological behavior. This study aims to establish a pre-mining ecohydrological baseline for watersheds located in the Mirai deposits, Zona da Mata Mineira. We monitored rainfall regimes and flow rates in four micro-watersheds weekly over one year, alongside seasonal water quality assessments and soil physical analyses (infiltration, moisture, and mechanical resistance). Results indicate that while watersheds followed regional seasonal rainfall patterns, unregulated anthropogenic water withdrawals completely disrupted the flow of Spring 1 during the dry season. Flow variability across the other springs was fundamentally dictated by spatial differences in soil physical properties and vegetation cover, contrasting the high infiltration but substantial biological water demand of native forests against specific pasture slopes. Water quality exhibited significant seasonal degradation driven by antecedent agricultural runoff. Crucially, although current physical analyses show soil compaction remains below critical thresholds, a near-perfect negative correlation ($r = -0.97$) between mechanical resistance and infiltration capacity was identified. This poses a severe predictive warning: future open-pit mining activities risk obliterating the fragile soil structure sustaining baseflow, making rigorous soil rehabilitation mandatory to ensure post-mining water security.

Keywords Streamflow, catchment management, ecohydrology, physicochemical parameters.

Introduction

The growing pressure on water resources, associated with changes in land use and land cover, intensifies the need for integrated planning and management of watersheds (Collischonn and Dornelles 2015). This management is essential to understand hydrological behavior and mitigate the occurrence of extreme events, ensuring water security and the conservation of river biodiversity (Vörösmarty et al. 2010). In this context, Hydrology plays a fundamental role in understanding the processes related to the occurrence, distribution, and quality of water, as well as its interactions with the physical and biological components of the environment (Collischonn and Dornelles 2015). To operationalize this monitoring, micro-watersheds constitute fundamental territorial units for environmental planning and monitoring, allowing the assessment of impacts resulting from anthropogenic alterations on water dynamics (Bosch and Hewlett 1982).

Among the economic activities capable of promoting severe alterations in hydrological processes, mining stands out. Despite its undeniable relevance to the development of emerging economies (Sonter et al. 2018), this activity has a high potential for degradation, especially in tropical regions, where the removal of native vegetation and the movement of regolith favor intense erosive processes (Bruijnzeel 2004). Brazil is among the world's largest producers of bauxite (Revista Alumínio 2019; USGS 2023), the extraction of which occurs mostly in open-pit mines. This mining technique leaves the surface highly vulnerable and exemplifies a drastic modification of the natural landscape, imposing significant challenges to environmental conservation.

The suppression of vegetation cover and soil exposure, intrinsic to mining, not only degrades the physical structure of the terrain but also substantially alters the processes of the local hydrological cycle (Grigg et al. 2017). Such modifications trigger profound disturbances in freshwater ecosystems, altering the mechanisms of groundwater recharge, storage, and discharge, in addition to contributing to the excessive input of sediments and contaminants (Castello et al. 2013; Yang et al. 2018). Similarly, Ping et al. (2017) demonstrated that mining activities directly influence the hydrological regime of watersheds, modifying flow patterns and surface runoff behavior. Consequently, water yield is severely affected, compromising baseflow, stream discharge, and the maintenance of springs in their areas of influence (Croton and Reed 2007; Sonter et al. 2018).

These hydrological alterations are strongly conditioned by the changes imposed on the physical-hydraulic properties of the soil. Machinery traffic and mining operations cause soil compaction, reducing porosity and increasing mechanical resistance to penetration (Hamza and Anderson 2005; Ralisch et al. 2008). These physical effects can persist for long periods (Drescher et al. 2016) and result in a drastic reduction in water infiltration rates into the soil, one of the most important indicators of the water storage capacity of micro-watersheds (Bono et al. 2012; Ceccatto et al. 2019). Conversely, areas that maintain the conservation of forest cover exhibit significantly more balanced hydrological behavior, conferring greater stability to water dynamics and protection against surface erosion (Ellison et al. 2017; Pinheiro et al. 2019).

Given the complexity of these interferences, systematic monitoring of affected watersheds through resource governance and water footprinting tools becomes imperative (Northey et al. 2016; Ali et al. 2017). Hydrological monitoring in the pre-mining stage is the crucial step that allows diagnosing natural conditions and establishing precise baseline parameters before any intervention occurs (Ping et al. 2017; Da Silveira et al. 2020). It is from the constitution of this primary database that it becomes possible to measure, in the future, the actual magnitude of the impacts caused by extraction and to subsidize effective strategies for environmental recovery and water resource management.

Considering the relevance of prior water planning in mineral exploration areas, this study focused on watersheds located in the Mirai deposits, in the Zona da Mata region of Minas Gerais state. The main objective of this research was to evaluate the hydrological behavior of springs and the physical characteristics of the soil in four micro-watersheds under a pre-bauxite mining scenario. Therefore, the aim is to answer how the original hydrogeological characteristics behave temporally, building a solid baseline database for future comparisons in post-mining scenarios.

Material and Methods

Study area

The research was conducted within the watersheds situated in the bauxite deposits of Mirai, in the Zona da Mata Mineira region (Fig.1). This specific location was chosen to facilitate the monitoring of spring flow hydrological regimes in a pre-mining scenario, providing a baseline for evaluating the potential impacts of bauxite mining activities managed by the Companhia Brasileira de Alumínio (CBA).

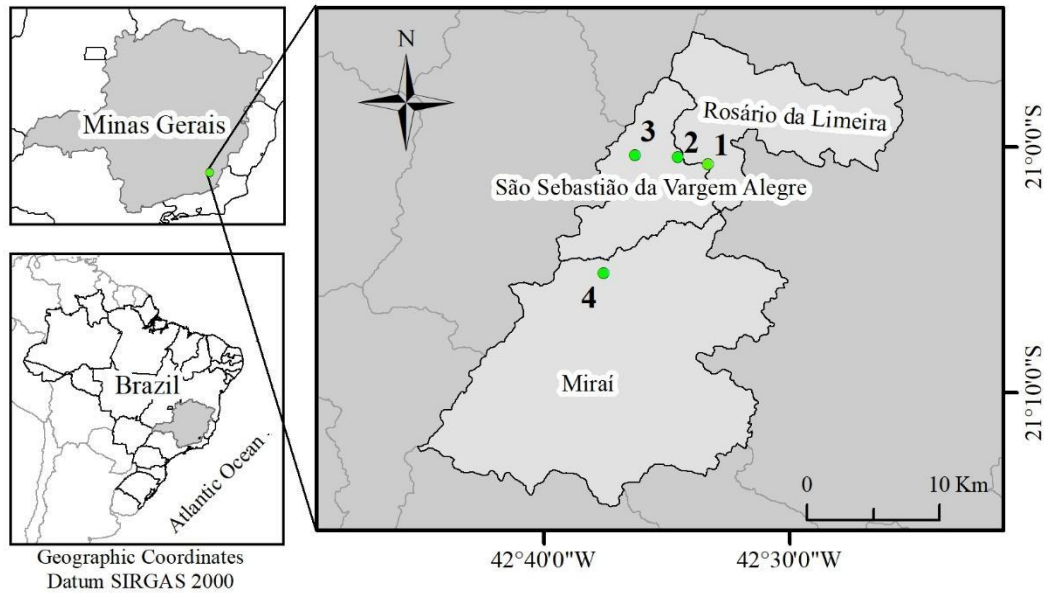


Fig. 1 Location of the study area and the evaluated springs. The inset maps on the left provide the regional context within Minas Gerais state and the national context within Brazil. The main map highlights the municipalities of Rosário da Limeira, São Sebastião da Vargem Alegre, and Mirai, where the numbered green points (1–4) represent the monitored springs. Geographic coordinates are based on the SIRGAS 2000 datum

To ensure a representative analysis, four micro-watersheds were established across the municipalities of Rosário da Limeira, São Sebastião da Vargem Alegre, and Mirai, within the State of Minas Gerais. The site selection process was governed by strict eligibility criteria designed to ensure experimental validity. These criteria included: (i) a reduced drainage area (ranging from 10 to 20,000 ha); (ii) a strategic and representative location concerning land use, land cover, geomorphology, and socioeconomic aspects; (iii) the consent and cooperative relationship with landowners; and (iv) operational feasibility, ensuring safe and consistent access for operators and equipment (Da Silveira et al. 2020).

Hydrological Monitoring and Soil Characterization

A comprehensive data collection campaign was executed weekly over a continuous one-year period, spanning from December 2022 to November 2023. This effort resulted in a total of 182 observations across 46 weeks, covering both meteorological and hydrological variables.

Precipitation and Flow Quantification

Precipitation dynamics were recorded using a custom-built PVC rain gauge with a 150 mm diameter, modeled after the specifications provided by Dias et al. (2013). To maximize accuracy, the apparatus was installed 1.50 m above ground level in an open area, sufficiently distant from canopy cover to prevent interception loss (Fig. 2). The precipitated volume was measured using a 1 L graduated cylinder, and the rainfall depth was subsequently calculated using Equation 1:

$$P \text{ (mm)} = \frac{V \text{ (L)}}{A \text{ (m}^2\text{)}} = \frac{V \text{ (L)}}{\frac{\pi D^2}{4} \text{ (m}^2\text{)}} \quad (1)$$

Substituting the diameter ($D = 0.150 \text{ m}$):

$$P \text{ (mm)} = \frac{V \text{ (L)}}{0,01767 \text{ (m}^2\text{)}}$$

Where: P = Rainfall depth (mm) V = Water volume collected (L) A = Catchment area of the rain gauge (m^2)



Fig. 2 Precipitation monitoring equipment. The image shows the custom-built PVC rain gauge (150 mm diameter) installed 1.50 m above ground level. The apparatus was positioned in an open area within the study site to ensure accurate rainfall depth (P) measurements by avoiding canopy interception

Concomitantly, spring discharge was quantified using two distinct methodologies: the direct volumetric method and the weir method. For Springs 2 and 3, the direct method was employed, which involved the construction of earthen dams equipped with a 150 mm PVC pipe outlet (Fig. 3). In this setup, water volume was collected in a 2 L graduated cylinder over a measured time interval (Equation 2).

$$Q = \frac{V (L)}{t (s)} \quad (2)$$

Where: Q = Flow rate (L/s); V = Volume collected (L); t = Time observed (s).



Fig. 3 Spring discharge measurement via direct volumetric method. The image details an earthen dam equipped with a 150 mm PVC pipe outlet established at the spring head. This setup was utilized for flow rate (Q) quantification by collecting water volume in a graduated cylinder over a measured time interval.

Conversely, Springs 1 and 4 were monitored using a triangular weir (Fig. 4), utilizing Equation 3. To facilitate a methodological comparison, data for Springs 1 and 4 were also collected via the direct method alongside the weir measurements.

$$Q = 1,40 H^{5/2} \quad (3)$$

Where: Q = Flow rate (m^3/s); H = Water head height (m).



Fig. 4 Streamflow quantification using the weir method. The image illustrates a triangular V-notch weir installed in the stream channel for discharge (Q) monitoring. This instrumentation allowed for continuous flow assessment during the pre-mining phase, providing a baseline for the evaluated micro-watersheds.

Water Quality Assessment and Pedological Analysis

Beyond quantitative hydrological metrics, water quality was assessed at three strategic intervals to capture seasonal variability: the dry season (August 2023), the rainy season (January 2024), and the post-rainy season (April 2024). Sampling was executed by the CBA water monitoring team, with subsequent physicochemical analyses performed by the company's Environmental and Soil Analysis Laboratory. These qualitative assessments enabled the calculation of the Water Quality Index (WQI), aggregating essential variables for priority uses, such as public supply and aquatic ecosystem maintenance.

Regarding soil physical properties, analyses focused on water infiltration rates, moisture content, and mechanical resistance to penetration (SMRP). Three random points were selected within each micro-watershed to represent different landscape positions: near the spring (Point 1), on the slope (Point 2), and at the hilltop (Point 3). Infiltration rates were determined utilizing a double-ring infiltrometer, with the resulting data adjusted via Horton's Equation (Equation 4) (Subramanya 2008). Simultaneously, soil moisture analysis adhered to the protocols outlined in the "Manual of Soil Analysis Methods" (Donagema et al. 2011), using disturbed samples collected via a Dutch auger for gravimetric determination (Equation 5). Furthermore, soil compaction profiles were generated using a digital penetrometer, measuring resistance up to a depth of 60 cm.

$$f = f_c + (f_o - f_c) \cdot e^{\beta t} \quad (4)$$

Where: f = Infiltration rate (mm/h); f_c = Infiltration rate at saturation (mm/h); f_o = Initial infiltration rate (mm/h); t = Infiltration time (min); β = Empirical parameter determined for each measurement over time.

$$U = \frac{(a-b)}{b} \quad (5)$$

Where: U = Gravimetric moisture (kg/kg); a = Wet sample mass (kg); b = Dry sample mass (kg).

Data Processing and Statistical Analysis

Upon completion of field data acquisition, all hydro-meteorological and pedological datasets were compiled and tabulated in Microsoft Excel. Initially, a descriptive statistical analysis was performed to generate mean flow and precipitation series, as well as to compute accumulated values for the monitoring period.

Subsequently, inferential statistical techniques were applied to discern relationships and differences between variables and sites. A linear correlation analysis (Pearson Correlation) was conducted to evaluate the interdependence of hydrological variables. To verify the statistical significance of these correlations, the Graybill F-test was employed. Furthermore, the Graybill F-test was utilized to compare the efficacy of the flow data collection methods (direct vs. weir) and to test for significant differences between monthly rainfall means across the four micro-watersheds. It is important to emphasize that flow and precipitation are hydrological variables exhibiting high temporal variability; therefore, in this hydrological context, they are treated as stochastic variables, precluding exact deterministic prediction of results (Collischonn and Dornelles 2015).

Results and Discussion

Hydrological monitoring revealed that the rainfall volume in the study region adhered to expected seasonal patterns for the Cwa humid subtropical climate, with an annual average approximating 1300 mm. The wettest months were from December 2022 to February 2023, whereas June 2023 witnessed negligible precipitation. This standard distribution—characterized by higher volumes between October and March and lower volumes from April to September—is critical for defining the baseline hydrological regime in tropical watersheds (Paiva et al. 2020; Zema et al. 2018).

Understanding this spatial and temporal precipitation variability is paramount to separate natural seasonal flow fluctuations from anthropogenic impacts in pre-mining baseline assessments (Ping et al. 2017; Silveira 2017). The Cwa climate imposes a dual stress on the hydrological system: intense summer storms test the landscape's vulnerability to surface runoff and erosion, while severe winter deficits test the resilience of deep percolation and baseflow maintenance. Accurately mapping these extremes is the foundational step before any open-pit extraction begins.

Regarding flow regimes, springs across the micro-watersheds maintained continuous discharge throughout the year, except for Spring 1, which ceased flowing between August and October 2023. The Graybill F-test (5% significance) confirmed a statistically significant difference in monthly rainfall means solely for Spring 1. However, paired flow and precipitation data demonstrated a positive Pearson correlation ($r = 0.63$), indicating that regional discharge naturally rises commensurately with precipitation. Therefore, the complete cessation of flow in Spring 1 during the dry season cannot be solely attributed to climatic drivers.

Table 1 P-values results for the statistical difference test between means (Graybill F-test) of monthly precipitation (mm) for the four micro-watersheds studied in the municipalities of Rosário da Limeira, São Sebastião da Vargem Alegre, and Mirai, Minas Gerais, December 2022 to November 2023.

Micro-watershed (Spring)	p-value			
	1	2	3	4
1	1	0.0303*	0.0000*	0.0000*
2	0.0303*	1	0.3445 ^{ns}	0.5761 ^{ns}
3	0.0000*	0.3445 ^{ns}	1	0.6410 ^{ns}
4	0.0000*	0.5761 ^{ns}	0.6410 ^{ns}	1

* Significant at 5%; ns: not significant.

The anomaly observed in Spring 1 is instead attributed to unregulated upstream water withdrawals by the property owner. This scenario highlights a critical vulnerability of headwater springs to unmonitored human interventions. Even during periods of expected low flow, these artificial demands can drastically break surface-groundwater interactions. Consequently, such unregulated withdrawals deplete baseflow resilience and create localized

hydrological drought conditions independently of the regional rainfall regime (Acosta et al. 2023; Castro and Gonçalves 2022; Martins et al. 2020).

Contrasting hydrological behaviors were observed among springs under similar land management, specifically pasture and cattle presence. Spring 3 exhibited the highest average flow (3.52 L/s) despite receiving the lowest accumulated precipitation. Conversely, Spring 1 recorded the highest accumulated precipitation yet yielded the lowest average flow. This divergence is fundamentally driven by the intrinsic spatial variability of soil physical properties and topographical features across the study area. These specific site characteristics dictate the efficiency of subsurface water storage and subsequent groundwater discharge to the springs.

Spring 3 benefits directly from higher groundwater availability and superior soil water infiltration rates on its slopes, significantly enhancing deep percolation that sustains baseflow even during prolonged dry spells. In stark contrast, the micro-watershed of Spring 1 suffers from shallower, poorly drained soils characterized by an inherently lower water storage capacity. These restrictive pedological features severely limit the system's ability to buffer and store rainfall inputs, increasing surface runoff and reducing underground yield (Bono et al. 2012; Silva-Parra et al. 2026; Thiengo et al. 2024).

Furthermore, Spring 4, situated in a native forest area, demonstrated an apparently paradoxical behavior: highly favorable soil permeability combined with lower relative surface flow. This phenomenon is a well-documented characteristic of complex forested watersheds. While native forests offer excellent physical soil structure that promotes rapid infiltration, their dense, multi-layered vegetation canopy intercepts a significant portion of rainfall before it ever reaches the ground. This initial interception significantly diminishes the effective precipitation available for subsequent soil recharge and baseflow generation.

Following the canopy interception, the deep and extensive root systems of the native forest function as continuous hydraulic pumps, maximizing both evapotranspiration and transpiration-driven water losses. Consequently, the forest consumes a massive volume of water to maintain its physiological processes. This inherent biological demand thereby reduces the available surface and subsurface water yield that feeds the spring, despite its high infiltration capacities (Penha et al. 2024; Pinheiro et al. 2019). This mechanism contrasts sharply with pasture lands, where lower transpiration demands frequently occur.

The quantification of streamflow using both direct and weir methods yielded highly reliable data across the monitored sites, allowing for precise polynomial equation adjustments based on monthly means. For instance, the coefficient of determination (R^2) for Spring 4 approached 0.97 for both methods. Although the Graybill F-test revealed statistical differences between the direct and weir methods ($p < 0.05$ for Springs 1 and 4), both techniques proved functionally robust and operationally viable for continuous pre-mining hydrological monitoring.

Accurate and continuous streamflow quantification through customized instrumentation is essential for generating reliable baseline datasets. In geomorphologically complex areas destined for future bauxite mining, the spatial distribution of these hydro-chemical data is absolutely necessary. This spatial resolution is required to accurately model individual headwater catchment functions and establish functional thresholds before extensive land-use changes obliterate the original topography. Establishing this precise baseline is the only reliable way to evaluate post-mining recovery success (Correa et al. 2019).

Water Quality Index (WQI) assessments classified all active springs as "Excellent" during the dry period. However, these classifications consistently downgraded to "Good" during the rainy and post-rainy seasons. This seasonal degradation—where specific parameters frequently exceed Maximum Permitted Values—is primarily associated with the mechanics of surface runoff in degraded landscapes. During intense summer storm events, the lack of protective vegetation in surrounding pasture areas leads to the rapid overland transport of suspended sediments and organic matter.

Such land use practices severely impact freshwater ecosystems by exponentially increasing contaminant input during rainfall (Castello et al. 2013; Sanga et al. 2026). Specifically, the marked fluctuation in phosphate concentrations across all watersheds, combined with biological contamination (coliforms and organic matter) in Spring 3, signals a strong legacy of antecedent agricultural pollution. These nutrient fluxes necessitate rigorous,

continuous monitoring to mitigate cumulative degradation in water bodies and ensure water security for downstream communities (Casson et al. 2025; Godoy et al. 2021; Hutchins 2023).

Baseline physical analyses encompassing infiltration rates, current moisture, and soil mechanical resistance to penetration (SMRP) were compared to standard reference values to provide context (Ceccatto et al. 2019; Drescher et al. 2016; Ralisch et al. 2008). Spring 1 (Pasture) exhibited low infiltration at Point 1 (surroundings) due to high moisture saturation from preceding rains. Point 2 (slope) exhibited higher infiltration despite high moisture, whereas Point 3 (hilltop) displayed low velocity. All monitored points exhibited medium compaction, remaining below critical structural degradation thresholds of 2000 kPa.

Regarding Spring 2 (Pasture), the spatial distribution of pedological attributes revealed low infiltration at Points 1 and 2, coinciding with high current moisture. Conversely, Point 3 showed elevated infiltration and moisture, a behavior attributed to its predominantly sandy soil texture that facilitates rapid water movement. While soil compaction remained at medium levels at Points 1 and 3, it reached its highest values at Point 2. This localized increase in mechanical resistance is likely due to specific surface and subsurface lithological variations (Bono et al. 2012; Santos et al. 2018).

The landscape dynamics in Spring 3 (Pasture/Steep slopes) demonstrated an efficient hydrological response at specific topographical positions. Points 1 and 2 presented the lowest SMRP values combined with high infiltration velocities and lower moisture content, indicating effective subsurface water flux. However, this optimal condition was not uniform. Point 3, situated at the hilltop, showed significantly greater soil compaction, higher moisture retention, and a correspondingly lower infiltration velocity, reflecting localized structural limitations that restrict deep percolation (Silva-Parra et al. 2026; Thiengo et al. 2024).

Finally, Spring 4 (Native Forest) maintained high soil moisture across all sampled topographical positions. Interestingly, Point 2 showed low infiltration velocity alongside the lowest penetration pressure, possibly resulting from pre-existing soil saturation. Point 3 presented high penetration pressure but simultaneously exhibited high infiltration velocity. This apparently contradictory behavior is attributed to the substantial volume of accumulated leaf litter typical of forested ecosystems. This litter layer dissipates rainfall kinetic energy and facilitates rapid initial water entry, preventing surface sealing even where deeper resistance exists (Mateus et al. 2013).

Table 2 Pearson Correlation Coefficient Matrix (r) for paired data of flow (L/s), precipitation (mm), SMRP (kPa), current soil moisture (%), and soil water infiltration rate (mm/h) in the municipalities of Rosário da Limeira, São Sebastião da Vargem Alegre, and Mirai, Minas Gerais, 2024.

Variable	r				
	Flow	Precipitation	SMRP	Soil Moisture	Infiltration Rate
Flow	1	0.63	-0.26	-0.29	0.27
Precipitation	0.63	1	-0.06	0.11	0.02
SMRP	-0.26	-0.06	1	0.11	-0.97
Soil Moisture	-0.29	0.11	0.11	1	-0.21
Infiltration Rate	0.27	0.02	-0.97	-0.21	1

Pearson correlations further elucidate these interdependent pedological and hydrological processes. Higher SMRP negatively correlated with flow ($r = -0.26$) and strongly hindered subsurface water movement, showing a near-perfect negative correlation with the infiltration rate ($r = -0.97$). This reaffirms the critical geomorphological principle that even moderate soil compaction drastically reduces hydraulic conductivity (De Correa et al. 2019). Interestingly, higher current soil moisture also correlated with lower spring flow ($r = -0.29$). This inverse relationship likely indicates the initial retention of water within the soil micropore matrix.

It is only after the soil profile reaches complete saturation that gravitational drainage effectively contributes to continuous baseflow maintenance. Establishing these precise pre-mining interdependencies is of paramount importance because the intended bauxite extraction represents a massive landscape disruption. Open-pit bauxite mining inherently necessitates the complete suppression of native vegetation and the extensive removal of the topsoil layer. Furthermore, these initial preparatory stages are immediately followed by intense, continuous heavy machinery traffic across the highly vulnerable exposed terrain.

Based on the strong negative correlation found between compaction (SMRP) and infiltration ($r = -0.97$), it is predictable that these activities possess a high potential to completely alter superficial soil structures. Without rigorous mitigation and soil rehabilitation strategies, mining operations will exacerbate existing hydrological disturbances, eliminating the fragile infiltration capacity currently maintaining the springs, converting potential recharge into highly erosive surface runoff, and ultimately threatening the region's water security (Ali et al. 2017; Northey et al. 2016; Sonter et al. 2018).

Conclusions

The monitored micro-watersheds exhibit a robust seasonal hydrological regime driven by precipitation, successfully establishing a clear pre-mining baseline. The localized cessation of flow in Spring 1, despite high accumulated rainfall, underscores the high vulnerability of headwater systems to unregulated anthropogenic water withdrawals, demonstrating that artificial demands can easily override natural climatic resilience.

Spatial variability in soil physical properties and land cover inherently dictates groundwater recharge and spring yield. While native forest areas ensure high initial infiltration due to a protective leaf litter layer, their substantial biological water demand limits surface yield compared to specific well-drained pasture slopes. Furthermore, the operational reliability of both direct and weir measurement methods confirms their viability for continuous baseline monitoring in these complex topographies.

Water quality assessments indicate significant seasonal degradation during rainy periods. This is primarily driven by surface runoff transporting suspended sediments and antecedent agricultural pollutants, such as phosphates and organic matter, from degraded pastures. This dynamic highlights the absolute necessity for continuous monitoring to ensure downstream water security before and during mining operations.

Crucially, current physical analyses reveal that soil mechanical resistance remains below critical degradation thresholds in the pre-mining scenario. However, the near-perfect negative correlation identified between soil compaction and infiltration capacity serves as a severe predictive warning. Given that open-pit bauxite mining inherently necessitates extensive topsoil removal and heavy machinery traffic, future operations risk completely obliterating the fragile soil structure currently sustaining baseflow. Therefore, successful post-mining recovery will depend strictly on the implementation of rigorous soil rehabilitation strategies capable of restoring these specific infiltration pathways and mitigating highly erosive surface runoff.

Acknowledgements

The authors are grateful to the Universidade Federal de Viçosa (UFV) for the institutional support provided. We thank the Companhia Brasileira de Alumínio (CBA) for granting access to the study area and for the logistical support regarding water quality analyses.

Fundings

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. and the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for the financial support.

Declarations

Conflict of interest the authors have no competing interests to declare that are relevant to the content of this article.

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