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Geochemical denudation in a scarp zone, upper das Velhas river, Quadrilátero Ferrífero, Minas Gerais, Brazil

Denudação geoquímica em zona de escarpa, alto rio das Velhas, Quadrilátero Ferrífero, Minas Gerais, Brasil

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Abstract: This study evaluates geochemical denudation in the upper course of das Velhas river, southern Quadrilátero Ferrífero, Minas Gerais - Brazil, within the Cachoeira das Andorinhas Environmental Protection Area. The local geology consists of metamorphic rocks from the Minas (Proterozoic) and the Rio das Velhas (Archean) Supergroups. A total of 23 surface-water samples were collected across different stream orders during both dry and wet season. Analyses included Atomic Spectrometry for major and trace elements, along with measurements of rainfall, pH, Eh and stream discharge. Elemental concentrations in solution follow the order: Na > Mg > Si > Ca > K > Al > Fe > As > Zn > Mn > Mo > Ba > Sr. The presence of gibbsite, combined with low concentrations of Al and Fe in solution, indicates a transitional stage between monosialitization to alitization. Lithology is the main control on denudation, with an average rate of 7.27 t/km²/year and vertical lowering of relief of 2.58 m/Ma. The results highlight the strong geological control over relief denudation in the region and provide essential parameters for unstinting landscape evolution.

Keywords: Geochemical denudation; Scarp zone; Quadrilátero Ferrífero.

Resumo: Este estudo quantifica a denudação geoquímica no alto curso do rio das Velhas, sul do Quadrilátero Ferrífero, Minas Gerais - Brasil, em área inserida na Área de Proteção Ambiental Cachoeira das Andorinhas. A geologia local é composta por rochas metamórficas dos Supergrupo Minas (Proterozoico) e Supergrupo Rio das Velhas (Arqueano). Foram coletadas 23 amostras de águas superficiais em diferentes hierarquias fluviais abrangendo os períodos seco e chuvoso. As análises incluíram Espectrometria de Emissão Óptica com Plasma Acoplado Indutivamente para quantificar os elementos maiores e traços, além das medições de precipitação, pH, Eh e vazão fluvial. As concentrações dissolvidas seguem a ordem: Na > Mg > Si > Ca > K > Al > Fe > As > Zn > Mn > Mo > Ba > Sr. A presença de gibbsita, associada aos baixos teores de Al e Fe em solução, indica estágio transicional entre a monossialização e alitização dos solos. A litologia constituiu o principal fator de controle da denudação, que apresenta de 7,27 toneladas/km^2/ano e taxa de rebaixamento vertical do relevo de 2,58 metros por milhão ao ano (m/M). Os resultados evidenciam forte controle geológico sobre a dinâmica geoquímica fluvial na região e oferecem parâmetros essenciais para o entendimento da evolução do relevo.

Palavras-chave: Denudação geoquímica; Zona de escarpa; Quadrilátero Ferrífero.

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1. Introduction

Geochemical denudation, driven by ionic transport, plays a central role in landscape evolution through process such as relief lowering, soil formation, and the long-term evolution of landforms (THOMAS, 1994; ANDERSON et al. 2002; BALOGH-BRUNSTAD et al. 2008). In tropical environments, its influence is particularly pronounced, strongly conditioning morphogenetic processes (SALGADO et al. 2007; VARAJÃO et al. 2009; ARUN et al. 2022). Pinet & Souriau (1998) have emphasized a direct relationship between chemical denudation and factors such as mean annual precipitation and relief slope, with significant implications for humid intertropical regions, such as the São Francisco river basin.

In geomorphology, denudation rates correspond to the volume of material removed from the surface and subsurface over time as a result of rock weathering (CARSON & KIRKBY, 1972; LEEDER, 1991; SOUCH, 2004). Research in tropical regions of Brazil, especially in the southeastern portion of the country, has advanced the understanding of denudational process by quantifying surface and subsurface mass removal rates associated with rock weathering (SALGADO et al. 2004; 2007; 2008; VARAJÃO et al. 2009; CHEREM et al. 2012; BARRETO et al. 2012; BERTOLINI, 2015; MARTINS, 2019). These studies indicate that lithology, climate, elevation range, mechanical erosion, soil type, and tectonic setting are key factors driving the variability of denudation rates.

Within the Quadrilátero Ferrífero (QFe), a mountainous domain in southeastern Brazil, the interplay of geology, geomorphology, and climate has shaped a complex, multiscale landscape (ALKMIM & MARSHAK, 1998; SALGADO et al. 2004; VARAJÃO et al. 2009; UHLEIN & NOCE, 2012; BEZERRA, 2014; BARROS et al. 2016). The region comprises distinct lithological units organized into four major groups (ENDO et al. 2019): (i) Archean crystalline basement, consisting of gneisses, granites, and migmatites; (ii) the Rio das Velhas Supergroup (Archean), composed of quartzites, schists, and phyllites in a greenstone-belt sequence; (iii) the Minas Supergroup (Proterozoic), made up of metasedimentary rocks such as quartzites, itabirites, schists, phyllites, and banded iron formations; and (iv) the Estrada Real Supergroup (Proterozoic), primarily formed by quartzites, metaconglomerates, and schists.

The intense erosion that has shaped the QFe landscape throughout its geological evolution has Motivated successive qualitative studies, beginning with the pioneering works of Harder & Chamberlin (1915a; 1915b). These authors attributed the region's altimetric variation (highlands, midlands, and lowlands) to differential lithological resistance, with quartzites and itabirites forming highlands, schists and phyllites underlying midlands, and granitic-gneiss complexes representing lowlands. Subsequent quantitative studies confirmed this lithological control, reporting erosion rates ranging from 1.3 to 4.0 m/Ma for quartzites and itabirites; 4.0 to 8.0 m/Ma for schists and phyllites; 5.5 m/Ma for granites and gneisses; and up to 25.0 m/Ma for marbles and dolomites (SALGADO et al. 2004). More recent research using isotopic data (^{10}Be) and topographic modeling (SL index) have refined this understanding, showing that lithologies traditionally considered resistant - such as quartzites and itabirites - do not always correspond to the highest topographic compartments (SALGADO et al. 2007; 2008; VARAJÃO et al. 2009; BEZERRA, 2014).

Studies by Bacellar (2000), Lipski (2002), Santos & Varajão (2004), Figueiredo et al. (2004), Bacellar et al. (2005), and Varajão et al. (2009) suggest that neotectonics and Cenozoic climatic fluctuations have influenced the geological and geomorphological evolution of the QFe. These processes have also affected the development of soil mantles, particularly through mechanisms such as colluviation (COSTA et al. 2013; 2014; COSTA, 2018). However, the influence of landforms on the development of pedological mantles remains poorly explored at the toposequence scale, especially regarding geochemical denudation rates and vertical lowering of steep slopes.

In this context, the present study focuses on analyzing the evolution of a soil system on escarpment slopes, building on the previous investigations of Costa et al. (2014) and considering long-term processes that control geochemical denudation and landscape lowering. The approach is based on elemental chemical quantification of the soil mantle and the geochemical signatures of surface waters in the upper course of the São Bartolomeu stream, a tributary of the upper das Velhas river. Thus, this research aims to enhance the understanding of interactions between pedogenesis and morphogenesis in highland and mid-altitude settings by determining geochemical denudation rates within the escarpment domain of the Quadrilátero Ferrífero, Minas Gerais.

2. Study Area

The study area comprises an escarpment zone with an elevation of 1,345 m and a slope gradient of 36%, located within the São Bartolomeu stream basin (upper Rio das Velhas basin) in the southern sector of the QFe (Figures 1 and 2a). This region lies within the Cachoeira das Andorinhas Environmental Protection Area (APA das Andorinhas), in the municipality of Ouro Preto, Minas Gerais, Brazil. It is underlain by Proterozoic metamorphic rocks aged approximately 2.5 Ga (Minas Supergroup) and Archean units dated between 2.6 and 2.7 Ga (Rio das Velhas Supergroup) (ALKMIM & MARSHAK, 1998; ENDO et al. 2019).

In the headwaters of São Bartolomeu basin (Figure 1), rock outcrops consist of quartzites and phyllites of the Caraça Group, as well as itabirites of the Itabira Group, both belonging to the Minas Supergroup (BALTAZAR et al. 2005). These lithologies are commonly overlain by ferruginous canga, which forms the regional summit surface, particularly over the Itabira Group itabirites (ZUCCHETTI et al. 1998; BALTAZAR et al. 2005). This domain is separated by a prominent break (step) in slope from a dissected, ridge and ravine landscape (IEF/UFV, 2005), which is sustained by schists of the Nova Lima Group (Rio das Velhas Supergroup). Within the study area, these schists have been subdivided into two units: (i) the Catarina Mendes Unit, consisting of homogeneous metagraywackes with subordinate rocks such as metaconglomerate lenses, tremolite-schists, and metaarenites; and (ii) the Córrego da Paina Unit, composed of metapelites, metasiltites, and metagraywackes.

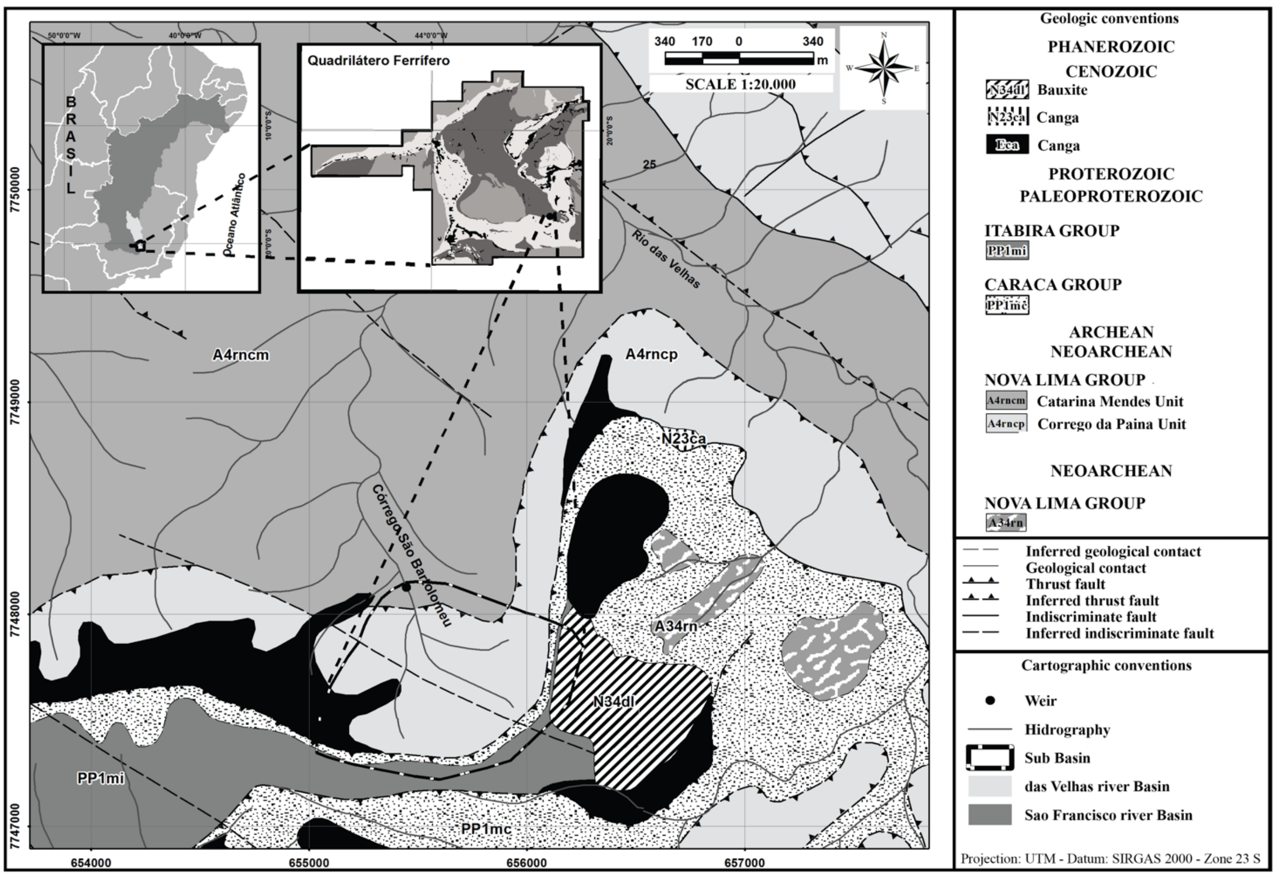

Figure 1 – Geological map of the São Bartolomeu stream basin, a tributary of the upper das Velhas river, in the Quadrilátero Ferrífero, Minas Gerais.
Source: Adapted from Baltazar et al. (2005) and Costa et al. (2014).

From a pedological perspective, the region current features dystrophic *Lithic Neosols* in the elevated areas, formed from the weathering of quartzites and itabirites (Itabira Group). On the lower slopes, dystrophic *Cambisols*, developed on schists (Nova Lima Group), are predominate (IEF/UFV, 2005; COSTA et al. 2014).

A study of a toposequence comprising five soil profiles by Costa et al. (2014) identified two distinct types of *Cambisols* on the mid and lower slopes, developed over units of the Rio das Velhas Supergroup. The upper slope was excluded from the analysis due to the presence of either exposed bedrock from the Minas Supergroup or talus deposits.

The first type, the older one, formed over colluvium and is separated from the in situ material by a stone line (SL), whose age, determined by optically stimulated luminescence (OSL), ranges between 6,000 ± 940 and 2,880 ± 465 years BP.The second, more recent soil type, lacks a stone line and displays Bi (weathered bedrock) and C (parent material) horizons that are lithologically dependent on the underlying schist (Nova Lima Group), indicating in-situ weathering of the parent material. The differential deposition of colluvium along the toposequence has been attributed to tectonic and climatic events that altered the local morphogenetic dynamics during the Quaternary (BACELLAR, 2000; FIGUEIREDO, 2000).

Chemical and micromorphological analyses reveal distinct differences in the genesis of the superficial horizons above and below the stone line (COSTA et al. 2013; 2014). These studies also demonstrate a process of vertical transformation of the schist into the Bi and C horizons, with no significant evidence of lateral internal translocation of material. The authors report low values for the $SiO2_2/Al_2O_3$ (Ki) and $SiO_2/(Al_2O_3 + Fe_2O_3)$ (Kr) ratios in horizons both above and below the stone line, indicating an intense process of desilication. Mineralogical analysis reveals that the clay fraction is predominantly composed of muscovite, kaolinite, and goethite (COSTA et al. 2013). The ubiquitous presence of kaolinite across all studied profiles denotes a pedogenetic environment dominated by monosiallitization (kaolinization).

According to the Köppen classification, the regional climate is tropical with distinct dry and wet seasons (Cwb), characterized by an average annual rainfall of 1,610 mm (data series 1988 – 2004) and a rainy season extending from October to March (CASTRO, 2006). These climatic conditions are conducive to the development of monosiallitized soils. The vegetation cover consists of *campo rupestre* (rupestrian grassland) on the summits of elevated geomorphic surfaces within the ridge and escarpment domain, and tropical forest on the slopes of the dissected ridge-and-ravine landscape (IEF/UFV, 2005).

3. Materials and Methods

3.1 Streamflow and Precipitation Monitoring

To obtain consistent hydrological data, a rectangular thin-plate weir with side contractions and free overfall was installed in the São Bartolomeu stream channel (UTM coordinates: 655468.92 E; 7748118.86 N; Zone 23K) (Figure 2C). The structure was constructed of galvanized steel according to the design proposed by the United States Geological Survey (USGS) (RANTZ, 1982). It was positioned in a second-order stream channel (STRAHLER, 1957) within an area free from anthropogenic disturbance.

Water level (stage) was recorded at two-hours intervals using a Schlumberger CTD-Diver® pressure transducer datalogger mounted on the weir wall (Figure 2C). Daily and monthly discharges (Q) were subsequently calculated using Equation 1, following the methodology recommended by the EPA (1997), Porto (2006), and Feitosa et al. (2008):

Equation 1:

$$Q = 1{,}83 * (L - 0{,}2\ h)h^{3/2}$$

Where:
Q = Discharge (m^3/s);
L = Weir width (m);
h = Height of water level above the weir base (m).

Precipitation data were collected concurrently at two-hour intervals using a Tracom-Watchdog 2900ET® meteorological station (Figure 2B), adhering to the technical guidelines of Garcez & Alvarez (1988).

3.2 Water Sample Collection and Processing

A total of 23 surface water samples were collected for chemical analysis during both the wet season (October 1, 2011, to March 31, 2012) and the dry season (April 1 to September 30, 2011). Samples were taken from the center of the channel in the vicinity of the weir using 25 mL syringes. They were immediately filtered through 0.45 µm cellulose-ester membranes and acidified with concentrated nitric acid (HNO_3) to a pH < 2, as prescribed by Greenberg et al. (1992). Following collection, all samples were stored at 4°C.

In-situ measurements of physicochemical parameters – hydrogen potential (pH), electrical conductivity (EC), redox potential (Eh), and temperature – were performed using a Myron-L Company 6PII-CE® multiparameter probe (Figure 2E). Prior to each measurement, the probe was conditioned by rinsing it three consecutive times with local stream water.

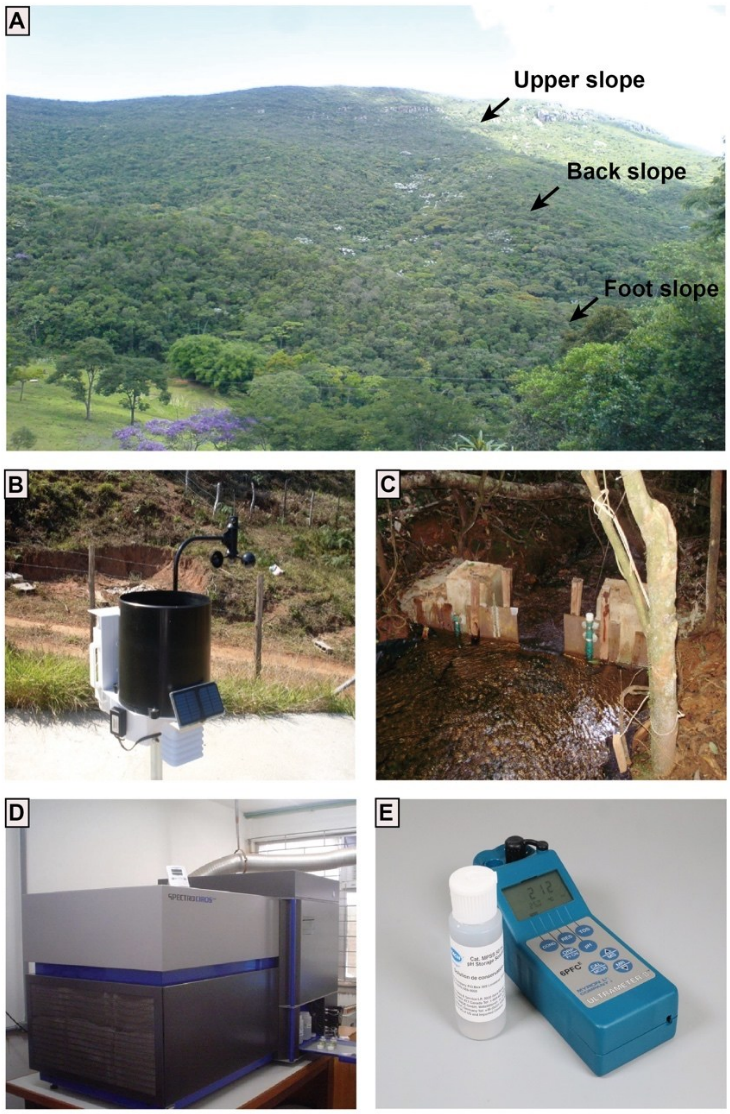

Figure 2 – Illustrative documentation of the methodological setup: a) the studied slope; b) the meteorological station; c) the weir installed on the São Bartolomeu stream where water samples were collected; d) the ICP-OES used to analyze water samples and quantify element concentrations; and e) the multiparameter probe employed for in-situ data collection.
Source: Authors (2025).

3.3 Inductively Coupled Plasma Optical Emission Spectrometry

The concentrations of chemical elements (Al, As, Ba, Ca, K, Fe, Mg, Li, Mn, Mo, Na, Sc, Si, Zn) were determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) using a SPECTRO CIROSCCD® 25000 instrument at the Environmental Geochemistry Laboratory (LQqA) of the Geology Department, School of Minas/UFOP

(Figure 2D). Analytical quality control was performed using certified reference material (CRM) for natural waters, specifically the NIST 1643e standard.

3.4 Geochemical Denudation Rate and Relief Lowering

The annual chemical denudation rate was estimated using an equation adapted from Thomas (1994), which accounts for the sum of the dissolved ionic load from both climatic seasons (wet and dry), in relation to the basin area, discharge, and sampled period:

Equation 2:

$$D = \frac{\left(\frac{CQ_u \times V_u}{A} \times T_u\right) + \left(\frac{CQ_s \times V_s}{A} \times T_s\right)}{d}$$

Where:
D = Denudation rate (ton/km^2/year);
CQ = Dissolved chemical load (ton/m^3);
u = Wet season;
s = Dry season;
V = Discharge (m^3/s);
A = Basin area (km^2);
T = Time converted to seconds;
d = Rock density.

Denudation rates were determined based on the chemical load measured via ICP-OES. For concentrations below the limit of quantification (LOQ), half the LOQ value was used in the calculations. The rate of relief lowering (m/Ma) was calculated using a rock density of 2.81 g/cm^3, as per Telford et al. (1990). The local lowering rate was estimated from the rates calculated for the entire upper basin.

4. Results

4.1 Hydrochemical Monitoring

Stream discharge increased by up to threefold in November and December 2011 and January 2012, coinciding with periods of higher precipitation (Figure 3). Discharge ranged between 16.95 and 89.89 m^3/s during the monitored period. Lower values (16.95 to 36.12 m^3/s) were observed from April to September (dry season), while higher values (22.57 to 89.89 m^3/s) occurred from October to March (wet season). Biweekly precipitation varied between 0 and 15.9 mm during the dry period and between 1.4 and 436.9 mm during the wet season. Electrical conductivity oscillated between 12.84 and 22.41 µS/cm (Figure 3).

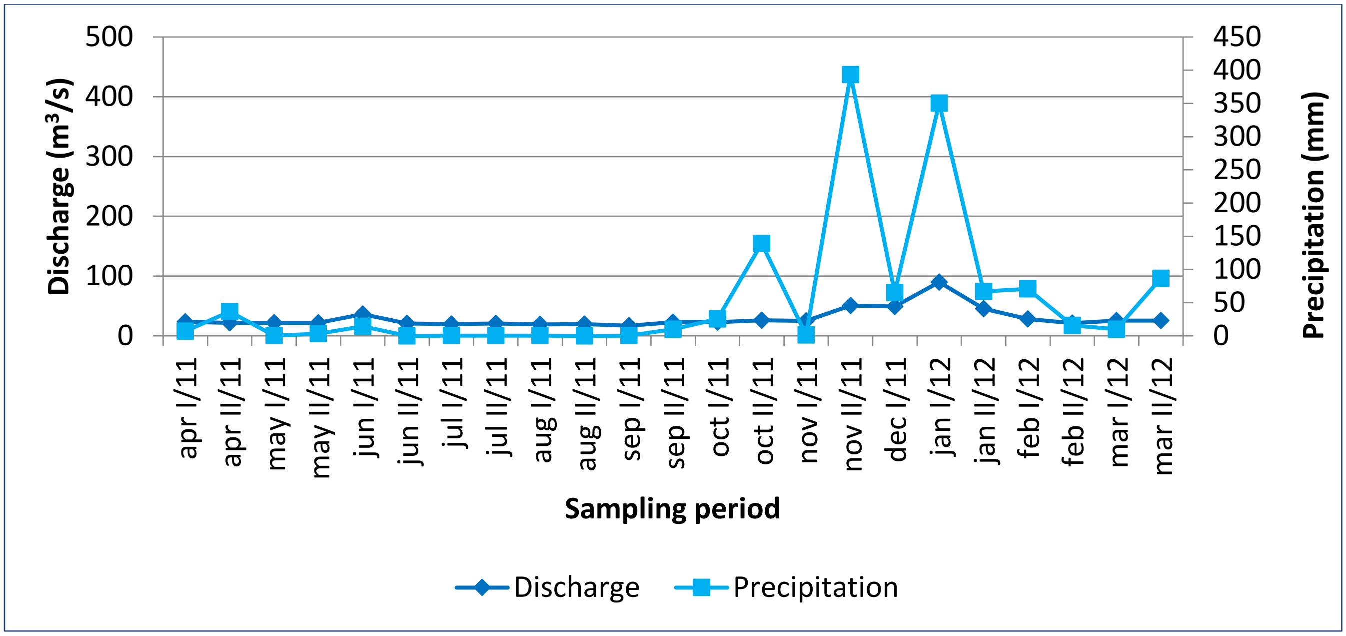

Figure 3 – Biweekly discharge and precipitation in the upper São Bartolomeu stream basin.
Source: Authors (2025).

4.2 Denudation Rates and Vertical Relief Lowering

The water samples were predominantly neutral to slightly alkaline, with redox potentials (Eh) between 68 mV and 279 mV, characterizing a reducing environment. Concentrations of metals and metalloids were generally below 1 mg·L⁻¹ (Table 1). The order of decreasing concentration in solution was: Na^{+}> Mg^{2+}> Si^{4+}> Ca^{2+}> K^{+}> Al^{3+}> Fe^{2+}> As^{5+}> Zn^{2+}> Mn^{2+}> Mo^{6+}> Ba^{2+}, Sr^{2+}.

Na and K showed marked seasonal variation, with concentrations up to 2.5 and 2.3 times higher, respectively, during the dry season (Table 1). Sodium values ranged from 0.5510 to 0.8160 mg·L^{-1} in the dry season and from 0.3384 to 0.5880 mg·L^{-1} in the wet season, reflecting an inverse relationship with discharge. Potassium also exhibited lower concentrations in the wet period, varying between 0.1838 and 0.4173 mg·L^{-1}. Calcium (Ca) and magnesium (Mg), associated with the schist lithology of the area (Nova Lima Group), showed higher concentrations. Ca ranged from 0.680 to 1.1670 mg·L^{-1}, especially during the rainy season, indicating greater solubility. Mg, in turn, maintained values between 0.808 and 1.246 mg·L^{-1} throughout the hydrological year, without significant seasonal differences.

The chemical denudation rate during the wet period was 2.051 ton/km^2/month, exceeding the dry period value of 1.587 ton/km^2/month by 0.464 ton/km^2/year (Figure 4). The influence of discharge on ionic load was evident, with the lowest rate observed in the second half of September (0.1016 ton/km^2/biweekly) and the highest in the first half of January (0.4233 ton/km^2/biweekly) (Table 2). The rate of vertical relief lowering determined for the area was 2.58 m/Ma.

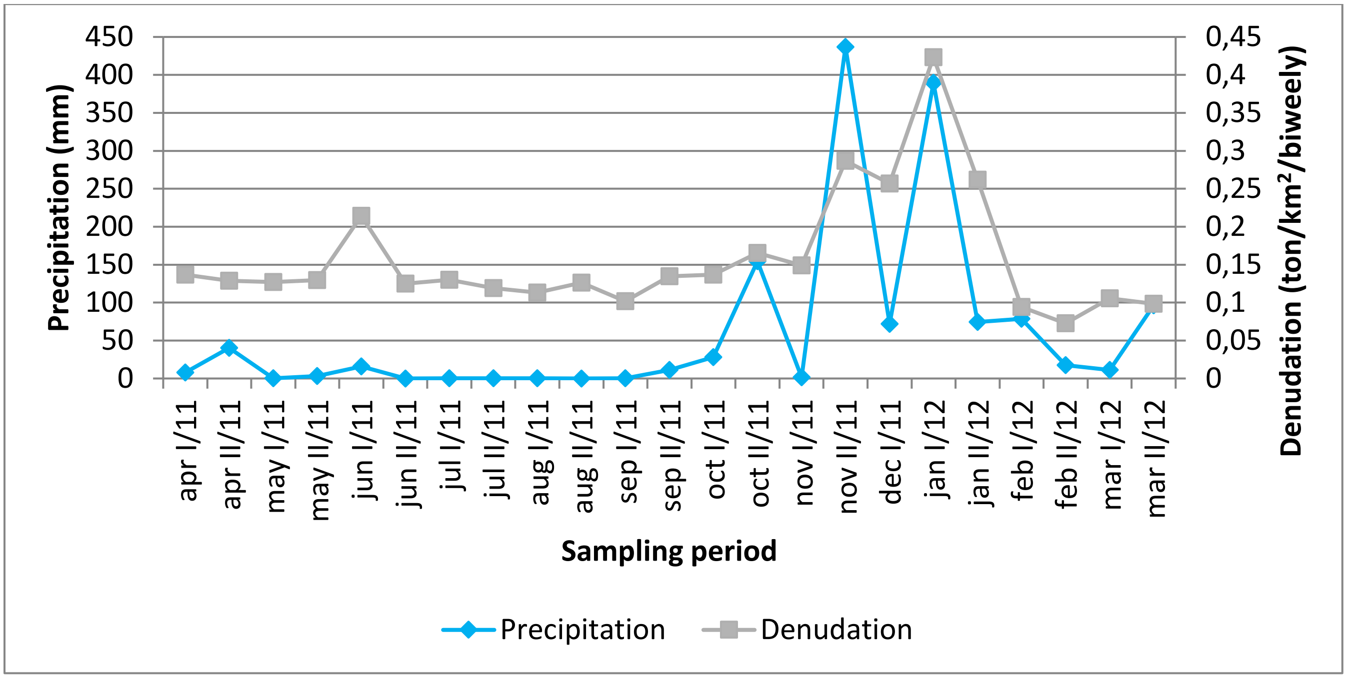

Figure 4 – Relationship between precipitation and denudation (ton/km²/ biweekly) during the dry and wet seasons. Source: Authors (2025).

Table 1 – Element concentrations, pH, and Eh in the upper São Bartolomeu stream.

Season	Period	pH	Eh	Al	Fe	Na	Ca	K	Mg	As	Ba	Mn	Mo	Li	Si	Sr	Zn	∑
			m/V								mg/L							
Dry	Apr I[1]	6,32	279	0,0136	0,0606	0,5510	0,6150	0,2427	1,064	0,028	0,0050	0,0258	0,0058	0,0004	2,200	0,0026	0,0017	4,8372
	Apr II[1]	6,83	216	0,0031	0,0249	0,5850	0,6420	0,2453	1,133	0,028	0,0053	0,0130	0,0058	0,0004	2,200	0,0028	0,0017	4,9436
	May I	6,92	165	0,0031	0,0187	0,5770	0,6080	0,2495	1,153	0,028	0,0050	0,0042	0,0058	0,0004	2,200	0,0027	0,0017	4,8940
	May II	7,80	140	0,0031	0,0190	0,5810	0,6150	0,2548	1,156	0,028	0,0048	0,0025	0,0058	0,0004	2,200	0,0026	0,0017	4,9422
	Jun I	7,45	80	0,0031	0,0155	0,5780	0,6410	0,2401	1,182	0,028	0,0049	0,0023	0,0058	0,0004	2,200	0,0027	0,0017	4,9442
	Jun II	7,85	68	0,0031	0,0206	0,5760	0,6720	0,2813	1,206	0,028	0,0050	0,0025	0,0058	0,0004	2,200	0,0028	0,0017	5,0660
	Jul I	6,93	157	0,0031	0,0135	0,6480	0,8660	0,4752	1,246	0,075	0,0058	0,0037	0,0058	0,0004	2,200	0,0028	0,0017	5,6079
	Jul II	7,75	167	0,0031	0,0203	0,5560	0,6690	0,2400	1,117	0,028	0,0046	0,0024	0,0058	0,0004	2,201	0,0026	0,0017	4,8129
	Aug I	7,51	164	0,0031	0,0234	0,5630	0,6800	0,2484	1,133	0,028	0,0048	0,0021	0,0058	0,0004	2,193	0,0027	0,0017	4,8503
	Aug II	6,42	221	0,0031	0,0262	0,8160	0,7340	0,4061	1,132	0,028	0,0047	0,0036	0,0058	0,0004	2,196	0,0028	0,0040	5,3253
	Sep I	6,56	216	0,0031	0,0202	0,5810	0,7410	0,2607	1,152	0,028	0,0047	0,0025	0,0058	0,0004	2,210	0,0028	0,0017	4,9748
	Sep II	6,53	211	0,0031	0,0187	0,5600	0,7220	0,2654	1,137	0,028	0,0045	0,0016	0,0118	0,0004	2,216	0,0027	0,0017	4,9398
Wet	Oct I	6,65	243	0,0031	0,0259	0,5700	0,7490	0,2968	1,185	0,028	0,0049	0,0024	0,0058	0,0004	2,259	0,0029	0,0017	5,0958
	Oct II	6,53	193	0,0120	0,0335	0,5880	0,9880	0,3038	1,140	0,058	0,0048	0,0034	0,0058	0,0004	2,216	0,0030	0,0096	5,3607
	Nov I	6,65	198	0,0031	0,0177	0,5720	0,8030	0,2545	1,182	0,028	0,0045	0,0025	0,0058	0,0004	2,193	0,0029	0,0017	5,0320
	Nov II	7,10	209	0,0031	0,0256	0,5480	0,7780	0,3369	1,030	0,028	0,0043	0,0043	0,0058	0,0004	2,007	0,0026	0,0017	4,7367
	Dec I	6,36	211	0,0031	0,0307	0,5290	0,7160	0,2467	0,973	0,028	0,0045	0,0047	0,0058	0,0004	1,863	0,0025	0,0057	4,3757
	Dec[2]II	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jan I	7,25	96	0,0092	0,0382	0,4835	0,7580	0,1838	0,808	0,028	0,0051	0,0047	0,0058	0,0004	1,644	0,0022	0,0195	3,9562
	Jan II	6,78	111	0,0124	0,0386	0,5960	0,9200	0,3478	0,920	0,028	0,0048	0,0042	0,0058	0,0009	1,821	0,0027	0,0170	4,8404
	Feb I	6,89	131	0,0031	0,0412	0,3384	0,9000	0,3255	0,994	0,028	0,0063	0,0112	0,0058	0,0008	2,000	0,0023	0,0017	4,7971
	Feb II	6,73	-	0,0031	0,0255	0,4927	0,8900	0,2426	1,079	0,028	0,0054	0,0030	0,0058	0,0009	2,000	0,0027	0,0017	4,8850
	Mar I	6,56	231	0,0031	0,0354	0,4291	1,1670	0,4026	1,208	0,028	0,0055	0,0084	0,0058	0,0010	2,000	0,0030	0,0151	5,4914
	Mar II	7,13	187	0,0031	0,0381	0,4356	0,9980	0,4173	1,211	0,028	0,0054	0,0076	0,0058	0,0011	2,000	0,0027	0,0017	5,2617

[1] I e II: denotes de first or second half of the month; [2]Sampled not collected.

Source: Authors (2025).

Table 2 – Discharge and total chemical denudation rates.

Season	Period	Discharge (m^3/s)	Denudation (ton/km^2/biweekly)
Dry	Apr I[1]	23.601,952	0,1369
	Apr II[1]	21.692,409	0,1286
	May I	21.664,939	0,1272
	May II	21.882,341	0,1297
	Jun I	36.122,357	0,2143
	Jun II	20.582,520	0,1251
	Jul I	19.469,024	0,1302
	Jul II	20.497,343	0,1190
	Aug I	19.332,751	0,1131
	Aug II	19.692,674	0,1263
	Sep I	16.945,627	0,1016
	Sep II	22.606,060	0,1345
Wet	Oct I	22.574,866	0,1369
	Oct II	25.916,020	0,1653
	Nov I	24.883,400	0,1490
	Nov II	50.851,245	0,2867
	Dec I	49.227,233	0,2566
	Dec[2]II	35.178,830	-
	Jan I	89.885,513	0,4233
	Jan II	45.455,827	0,2619
	Feb I	28.262,316	0,0941
	Feb II	21.141,893	0,0726
	Mar I	25.449,635	0,1057
	Mar II	25.330,657	0,0983

[1] I e II: denotes de first or second half of the month; [2]Sampled not collected.

Source: Authors (2025).

5. Discussion

Soils in southeastern Brazil are characterized by intense chemical and biological weathering, involving incongruent dissolution of primary into secondary minerals, slightly acidic pH, and low concentrations of alkali and alkaline-earth metals (DUNNE, 1978; EVANGELOU, 1998; KAMPF et al. 2009).

The high concentration of Si in solution suggests its ongoing solubilization (Table 1). Under deep weathering conditions, 1:1-type silicates dissolve and Si are leached (PEDRO & MELFI, 1977). Desilication, in turn, promotes the relative enrichment of Al and Fe in the regolith. The low concentrations of dissolved Al and Fe indicate that these elements are predominantly retained in the regolith, likely as (hydr)oxides, especially at pH above 5.6 (Table 1) and under oxidizing conditions (THOMAS, 1994). The presence of gibbsite ($Al(OH)_3$) alongside kaolinite ($Al_2Si_2O_5(OH)_4$) in the area's soils, detected in all profiles, suggests a transitional stage between monosiallitization (kaolinization) and allitization (COSTA et al. 2014). Generally, feldspars and micas present in the parent material control Si (as silica) concentrations in early weathering stages. The partial hydrolysis of primary silicates in humid, well-drained environments favors the presence of 1:1 clays, such as kaolinites. This clay mineral was detected in all profiles (P1 to P5) of the toposequence described by Costa et al. (2014). The persistence of kaolinite in the study area may be attributed to incorporation of newly exposed colluvial material (ESPÍNDOLA, 2013).

Mass movements are frequent in southeastern Brazil due to steep relief and deforestation over the last 250 years. Consequently, soils developed on slopes, terraces, and plains receive eroded material from i- upstream (VIEIRA et al. 2025); and/or ii- biogeochemical cycling (FAURE, 1991; JOBBÁGY & JACKSON, 2004; FONTES, 2012). Phytoliths, produced throughout the lifespan of most plants, are incorporated into the soil upon plant death. After incorporation, phytoliths partially or completely decompose, replenishing soil silicon (BENVENUTO et al. 2025). Animals, such as termites, also cycle Si through the soil via bioturbation. The selection and mixing of clay particles from deeper horizons to the surface ensures Si replenishment (JOUQUET et al. 2020).

The concentration of alkali and alkaline-earth metals (Ca, Mg, K, Na) is sustained by the weathering of feldspars when present, and in advanced weathering stages, by weak adsorption onto silicate clays or complexation with soil organic compounds (KABATA-PENDIAS, 2011; ALLOWAY, 2013). Weathering leads to the destruction of base-containing minerals like Na-bearing phases, and the leaching of this cation reduces its average content from 1.30 wt.% in fresh rock to only 0.02 wt.% in completely weathered regolith (FAURE, 1991).

Soils with an incipient degree of development, such as Cambisols, have a chemical composition strictly associated with the parent material (BURAK et al. 2010; SOUZA et al. 2015). In the study area, these soil classes derive primarily from the weathering of schists, a rock with low plagioclase content (PEDROSA-SOARES et al. 1994; DARDENNE & SCHOBBENHAUS, 2001). Reinforcing this, chemical analyses of unweathered Nova Lima Group schist (Córrego da Paina Unit – correlative to the Catarina Mendes Unit) by Varajão et al. (2009) revealed lower contents of calcium, sodium, and potassium, and elevated concentrations of silicon, iron, aluminum, manganese, and magnesium. Thus, soils developed on these materials exhibit dystrophy inherited from the parent material, as initially indicated by Costa et al. (2014) through routine chemical analyses. In this context, Varajão et al. (2009) observed a correlation between the concentration of certain elements in weathering profiles and their concentrations in waters within the QFe. Generally, the authors noted an enrichment of Fe, Al, and Mn and a depletion of K along the weathering profiles.

Consistent with observations in weathering profiles by Costa (2018), Fe, Al, and Mn exhibited low concentrations in the waters. Conversely, the distribution of Na, Ca, and Mg in the profiles is irregular, showing no linear trend, which reflects mineralogical variations among lithotypes and the low soil maturity. These elements show high concentrations in the waters, attesting to their high mobility, a fact corroborating trends also observed in this research (Table 1).

The geochemical denudation rate showed substantial variations during certain fortnights of the wet and dry seasons (Table 2). For instance, the denudation rate in January was significantly higher (0.4233 and 0.2619 ton/km^2/fortnight) than in February (0.0941 and 0.0726 ton/km^2/fortnight), both within the wet season. Therefore, annual denudation should be calculated based on more frequent sampling. Regarding studies on chemical denudation rates, research by Barreto et al. (2012) on similar rock substrates (quartzite and schist) in the São Francisco River basin (Serra do Espinhaço), located north of this study area, revealed an average denudation of 3.10 ton/km^2/year (São Francisco basin 7 - SF7), lower than the 7.27 ton/km^2/year found in this study (Table 2). Given that both areas are under a similar climatic regime, this difference can be explained by the fact that the microbasin in this study is located in a headwater zone, thus having higher erosive energy.

In studies by Salgado et al. (2004) on basins with lithotypes belonging to the Rio das Velhas and Minas Supergroups (Córrego da Esperança and Cata Branca basins), relief lowering rates ranging between 3.69 and 3.91 m/Ma were found in QFe regions classified as high and mid-altitude lands by Harder & Chamberlin (1915). Considering the lithological, geomorphological, climatic, and pedological similarities between these regions, a comparison with the result obtained here of 2.58 m/Ma is permissible. Therefore, these data are consistent with the general average lowering rates for more resistant and moderately resistant lithologies (≈ 1.3 – 8 m/Ma) postulated by Salgado et al. (2004).

Ferrier & Kirchner (2008) suggested that the chemical denudation rate has a linear relationship with the physical erosion rate up to a point, due to the constant exposure of fresh rock at the surface, beyond which the chemical denudation rate decreases. The authors also suggest that periodic erosion events, interspersed with stability and soil formation, ensure low but above-zero chemical denudation rates, as verified in this study where the total geochemical denudation rate was 7.27 ton/km^2/year. This scenario could favor the deepening of the weathering mantle, albeit with characteristics of a dystrophic, macromorphologically poorly evolved soil (COSTA et al. 2014) and micromorphologically (COSTA et al. 2013), as observed in Cambisols.

6. Conclusions

To understand the relationships between pedogenesis and morphogenesis in an escarpment zone of the upper São Bartolomeu stream, a tributary of the upper das Velhas river, chemical denudation rates were determined. The study found a value of 7.27 ton/km^2/year and a vertical relief lowering rate of 2.58 m/Ma. This rate is similar to results from other studies in southeastern Brazil, where lithology and climatic conditions are comparable.

The results also revealed that the chemical denudation rate during the wet period exceeds that of the dry period by 0.714 ton/km^2/year. Given that these denudation rates can vary significantly across seasons, a high sampling frequency is recommended to obtain more accurate annual rates. Furthermore, low concentrations of metals and metalloids in surface waters were observed, attributed to the chemical poverty of the soil parent material and the deep weathering of the regolith.

Hydrochemical data also indicated greater solubility of Si and base cations compared to Al, Fe, and Mn, confirming the process of desilication in the studied area. These results corroborate previous geochemical interpretations from watercourses in the upper das Velhas river and confirm that river waters can effectively capture the geochemical signature of the lithotypes they drain and even of the soils they traverse.

This body of evidence confirms the direct influence of differential erosive processes, here addressed from a geochemical perspective, and of the vertical relief lowering rate on local pedogenesis. The influx or removal of material within the system directly interferes with the incompleteness of pedogenetic processes that characterize slope mantles in escarpment areas. Under these conditions, soils remain chemically poor and pedogenetically immature.

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