https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 24, nº ESPECIAL (2023)

http://dx.doi.org/10.20502/rbg.v24i00.2326

Research Article

Eucalyptus Plantations in Pasture Matrix and Erosive Reactivation of Gullies in the Sesmaria River Basin (SP/RJ): a cycle of instability in headwater valleys

Plantios de Eucalipto em Matriz de Pastagem e Reativação Erosiva de Voçorocas na Bacia do Rio Sesmaria (SP/RJ): um ciclo de instabilidade em vales de cabeceiras

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Received: 12/12/2022; Accepted: 12/09/2023; Published: 28/09/2023

Abstract: In the 21st century, eucalyptus plantations have expanded in the middle valley of the Paraíba do Sul River, in the southwestern region of Brazil, replacing degraded pastures. Some studies associate these plantations with the reduction of groundwater levels, but field observations have indicated that erosive activity related to underground water flows is more significant. This study focuses on the reactivation of erosive processes leading to the regressive growth of gullies after the introduction of eucalyptus in pasture areas. Infiltration experiments, soil suction monitoring, well water levels measurement, and gully erosion assessment were conducted after the introduction of eucalyptus. The results indicated that eucalyptus cover facilitated rainwater infiltration, feeding temporary and suspended aquifers. These flows, combined with the permanent aquifer, caused erosion due to excessive pressure on gully margins, bottoms, and slopes. The high erosion rates decreased over the years after the introduction of eucalyptus. Tree vegetation began to recover in the gullies, indicating a trend towards stabilization. In response to changes in land use, the drainage and erosion system are undergoing an internal adjustment period in search of a new balance and stability.

Keywords: eucalyptus; gully; permanent regional aquifer; temporary suspended aquifer; exfiltration faces.

Resumo: No século XXI, os plantios de eucaliptos expandiram-se no médio vale do rio Paraíba do Sul, substituindo pastagens degradadas. Alguns estudos associam esses plantios à redução do nível d'água subterrânea, mas observações de campo indicaram que a atividade erosiva, causada por mecanismos relacionados aos fluxos de água subterrânea é significativa. Este estudo foca na reativação dos processos erosivos que levam ao crescimento regressivo de voçorocas após a introdução de eucaliptos em áreas de pastagens. Foram realizados experimentos de infiltração, monitoramento da sucção no solo, medição dos níveis d'água em poços e avaliação da erosão nas voçorocas após a introdução dos eucaliptos. Os resultados indicaram que a cobertura de eucaliptos facilitou a infiltração da chuva, alimentando aquíferos temporários e suspensos. Esses fluxos, combinados com o aquífero permanente, causaram erosão devido à pressão excessiva nas margens, fundo das voçorocas e encostas. As altas taxas iniciais de erosão, logo após a introdução dos eucaliptos, foram reduzindo ao longo dos anos. A vegetação arbórea começou a se recuperar nas voçorocas, indicando uma tendência à estabilização. Em resposta às mudanças no uso da terra, o sistema de drenagem e erosão passa por um período de ajuste interno em busca de um novo equilíbrio e estabilidade.

Palavras-chave: eucalipto; voçoroca; aquífero regional permanente; aquífero suspenso temporário; faces de exfiltração.

1. Introduction

The estimated area of planted forests in Brazil reached a total of 94,868.39 km² in 2021, 76.9% of which is covered by eucalyptus, concentrated in the Southeast region of the country (PEVS/IBGE, 2022). In the transition to the 21st century, patches of eucalyptus were introduced into a degraded pasture matrix and, in some cases, close to patches of secondary forest in the domain of hills of the middle valley of the Paraíba do Sul River (MVRPS), between the states of São Paulo and Rio de Janeiro (VIANNA; COELHO NETTO; SATO, 2009). In the mapping from satellite images of the Paraíba do Sul river valley region, in the São Paulo state portion, produced by Ronquim and Cocharski (2016ab), eucalyptus patches covered 352 km² in 1985 and reached a total of 1,136 km² in 2015 (8.1% of the total 13,974 km² of mapped area) advancing mainly under former pasture areas. A large part of the eucalyptus trees in the region are destined for the pulp and paper sector, being cloned, hybrid individuals, resulting from two species of the genus *Eucalyptus* (*E. urophylla x E. grandis*). The plantations have uniform age and spacing, usually with rotations of less than eight years, and occupy the drainage dividers and lateral slopes of low-hierarchical valleys (or drainage headwaters) where, at the bottom of these valleys, secondary vegetation prevails (native to the Atlantic Forest) in different stages of regeneration, as buffer zones of the river channel network (SATO; AVELAR; COELHO NETTO, 2011).

After a period of approximately one hundred years with the use of extensive pasture in rural areas of the region, the growth of eucalyptus monoculture has promoted an accelerated process of transformation in land use and land cover (SATO, 2008; VIANNA; COELHO NETTO; SATO, 2009; RONQUIM; COCHARSKI, 2016ab). The possible effects of this change in the hydro-erosive dynamics within the eucalyptus plantation areas and surroundings remain open. During field trips through the Paraíba do Sul River valley region, in 2004, the authors observed evidence of intense erosive activity due to the action of subsurface water on exfiltration faces related to highway cuts downstream of eucalyptus plantations. This fact called attention since, usually, eucalyptus is attributed a function of extracting or drying water from the soil and decreasing the flow of water in the channels (streamflow), as well as the lowering of the water table level in response to the inhibition of recharge of aquifers (VAN LILL; KRUGER; VAN WYK, 1980; LIMA et al., 1990; SCOTT; LESCH, 1997; ZHOU et al., 2002; ALBAUGH et al., 2013; OUYANG et al., 2016), which, in principle, would not induce this type of erosion.

In this context, the introduction of eucalyptus plantations in the region was initially evaluated as a possible change favorable to the lowering of the regional aquifer, capable of slowing down or stabilizing erosion caused by groundwater and the growth of gullies. However, after the insertion of these plantations in the Sesmaria River basin (149 km²), the erosive reactivation of incised channels of the gully type, which were previously stabilized, was observed (SATO, 2012; FACADIO, 2016). This finding stimulated the development of research aimed at greater knowledge and explanation of the role of eucalyptus plantations in hydrology and erosion, with attention to the expansion of the channel network and the retreat of slopes.

The initial focus of the research was the recognition of the interception of rainfall on the slopes under eucalyptus plantations and, in an unprecedented way in the literature, it was verified that below the canopy there is an increase in water flows along the trunk, due to the architecture of converging branches and intense dripping, resulting in a concentration of rainwater that, on average, reaches 160% of the quantity measured above the tree canopy, occasionally reaching up to 567% (SATO et al., 2011). Melos, Sato, and Coelho Netto (2010), in this same basin, observed in the period from October 2006 to September 2008, that the average production of accumulated plant litter was 8.4 Mg. ha^{-1}, of which 10.2 Mg. ha^{-1} on the divider and 6.6 Mg. ha^{-1} on the lateral slope. These same authors indicate that the water retention capacity of the eucalyptus litter reaches an average value of 235%, that is, close to the average values found in the Tijuca Forest (RJ) between 259% (MONTEZUMA, 2005) and 200% (MIRANDA, 1992). The decomposition coefficient is low (CD=0.39) due to the microclimate and reduced decomposing fauna (SATO, 2008). The predominance of pivotal rooting of these eucalyptus species was also highlighted as a relevant factor in the preferential percolation of water in the soil, similar to what was indicated by Silveira et al. (2005) in tropical humid hillside forests. Some questions unfolded from these studies, taking into account the interaction that eucalyptus plantations have with water: what is the influence of these plantations on the hydrological and erosive behavior of the slopes?

Previous research in the Bananal River basin (518 km^2), close to the Sesmaria River basin and with a similar erosion mechanism in the evolution of the channel network, pointed to intense erosive activity associated with the regressive growth of the channel network through the headwater valleys, in a spatially non-uniform evolutionary pattern (COELHO NETTO, 2003). The morphology of incised channels with variable depths and widths, which can exceed 30 meters, resulting from erosion mechanisms due to excess pore-pressure on the exfiltration face of underground water flows, configures what was called "voçoroca" by Pichler (1953). The axes of the headwater drainage valleys, in turn, are guided by sub-vertical rock fractures, which constitute the main routes for the exfiltration of groundwater flows by artesianism, whose discharges reflect variations in the pressure head in depth in the zone saturated (COELHO NETTO, 2003). The temporal variability of the pressure head in the aquifer does not respond directly to local rainfall inputs, delaying from two to four months concerning regionally accumulated rainfall, as attested by monitoring in different locations of the referred basin (AVELAR; COELHO NETTO, 1992a; 1992b; FONSECA, 2006; ROCHA LEÃO, 2005; LEAL; COELHO NETTO; AVELAR, 2015).

This article aims to understand and explain the role of eucalyptus plantations in the hydrological and erosive dynamics of the slopes, in the hilly domain of the middle valley of the Paraíba do Sul River. To this end, the Sesmaria River basin was selected as a laboratory area for field research, with a focus on the drainage headwater valleys located on farms that had the insertion of eucalyptus at the beginning of this century. Attention is focused on understanding the effects of planting eucalyptus on the hydrological behavior of the unsaturated and saturated zone and on assessing the extent of the effects of introducing eucalyptus in the basin. As a complement, monitoring of erosion rates related to the growth and retreat of gullies in headwater valleys adjacent to eucalyptus plantations was included. It is worth mentioning that the erosive channels of the two gullies were stabilized and were reactivated concomitantly with the change in land use with the introduction of eucalyptus. Regionally, these plantations were introduced following a spatial pattern in isolated patches over a matrix of grasses (extensive pastures) with sparse fragments of degraded secondary forest (VIANNA; COELHO NETTO; SATO, 2009).

2. Study Area

The Sesmaria River basin (149 km^2) drains the reverse of the Serra do Mar Atlantic escarpment, on the right bank of the middle valley of the Paraíba do Sul River (MVRPS) between the coordinates 22° 28' and 22° 43' S/ 44° 35' and 44°26' W, presenting a topographic slope of 1,695 m (2,095 m to 400 m) and a high topographic gradient of 0.05 (dimensionless, $m \cdot m^{-1}$) (SATO, 2008). The basin is divided into two geomorphological compartments: the hilly domain, with altitudes below 600 m, and the mountainous domain, with higher altitudes and relief amplitude > 300 m. According to Sato (2008), the average annual rainfall in the mountainous domain varies by around 1,996 mm, while in the hilly domain, it varies around 1,509 mm. The months from October to March have average monthly rainfall above 100 mm and accumulated accounts for approximately 80% of the annual total for both domains (hills and mountains). The driest months are June, July, and August, with monthly averages below 50 mm.

As for the use and coverage of the Sesmaria basin (Figure 1), it is worth noting that the eucalyptus plantations spread across the hilly domain, while the Atlantic Forest fragments, which in total correspond to 31.7% of the basin area, are more concentrated in the mountain compartment; in the hilly domain, there are small and numerous fragments. According to Sato (2008), the matrix of the landscape of this basin, as well as that found throughout the MVRPS, is grasses intended for extensive livestock, totaling 63.5% of its area; only 1.6% of the basin's area corresponds to urban occupation (in expansion) of the city of Resende (RJ), to the north, in the basin's outlet at the confluence with the Paraíba do Sul River.

The rivers that drain the reverse of the Serra do Mar escarpment towards the Paraíba do Sul River, among them the Sesmaria River, have their formation and growth under strong structural control of the underlying rocks. Regarding geological aspects, pre-Cambrian rocks predominate, represented by the Embu and Taquaral complexes, in addition to the Campo Alegre suite, with NE-SW orientation. In the metasediments of the Embu complex, a series of antiformal and synformal folds are identified. Tertiary rocks are observed in the Resende sedimentary basin and Quaternary deposits are found on the terraces and floodplains of the Feio, Formoso, and São João tributary rivers, in addition to the main valley in areas close to its confluence with the Paraíba do Sul River. The Sesmaria River drains in the NE direction following the orientation (strike) of the underlying geological layers; in its medium-low course, there are changes in orientation at the intersection with faults oriented towards NNW (EIRADO SILVA et al, 1993; EIRADO SILVA, 2006).

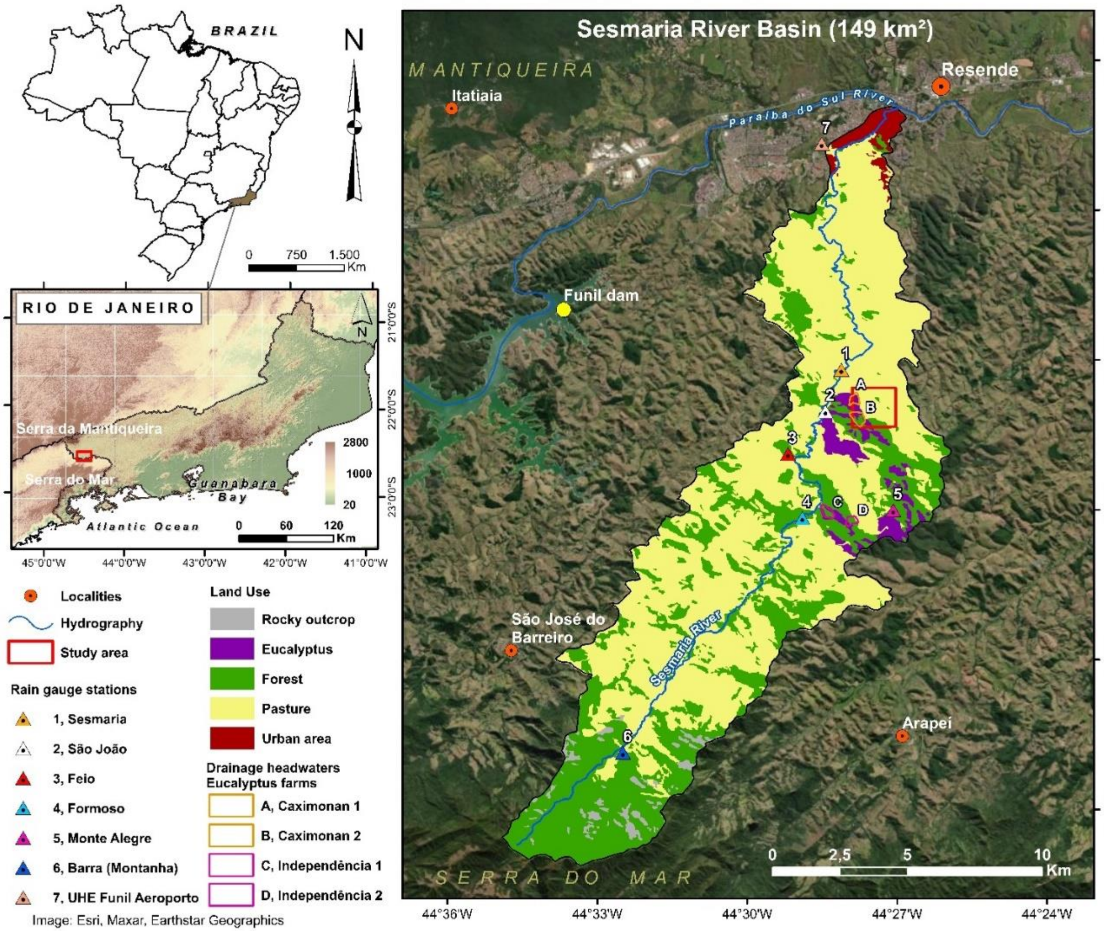

Figure 1. Location and land cover of the Sesmaria River basin, highlighting the study area in red.

In the central portion of the Sesmaria River basin are located the small drainage basins, which correspond to the headwater valleys selected for the installation of field monitoring stations with eucalyptus plantations. The stations are located on two farms controlled by the company Fibria (currently Suzano Papel e Celulose SA): Caximonan and Independência (Figure 2). The characteristics of use and coverage, as well as the geomorphological parameters of the monitored headwaters, are listed in Table 1. In this same basin, the Monte Alegre farm (22° 36' 26.94" S; 44° 27' 2.92" W) was also selected for surface runoff studies. Plantings were introduced at Caximonan and Independência farms in March and April 2004, respectively, with spacing of 3 x 2 m or 3 x 1.5 m, which results in great homogeneity for planting. Table 2 presents the parameters of the eucalyptus plantations carried out by the company Fibria. Routinely, throughout the development of the plantations, fertilization, chemical weed, and ant control were carried out. These eucalyptus plantations were not cut when they were seven years old, as previously foreseen, due to impediments by the environmental agency (INEA-RJ).

At the Itamarati farm, located on the opposite slope of the Caximonan farm, field activities were carried out for hydrological monitoring and the erosive expansion of channels by gullying (**Figure 3**). In this farm, an extensive dairy livestock activity prevailed, in the traditional molds of the MVRPS, presenting a matrix of grass of the genus *Brachiaria*. The history of land use on this farm follows the cycle of direct replacement of the Atlantic Forest by coffee cultivation during the 19th century and, later, by grasses destined for extensive livestock farming throughout the 20th century with degraded pastures.

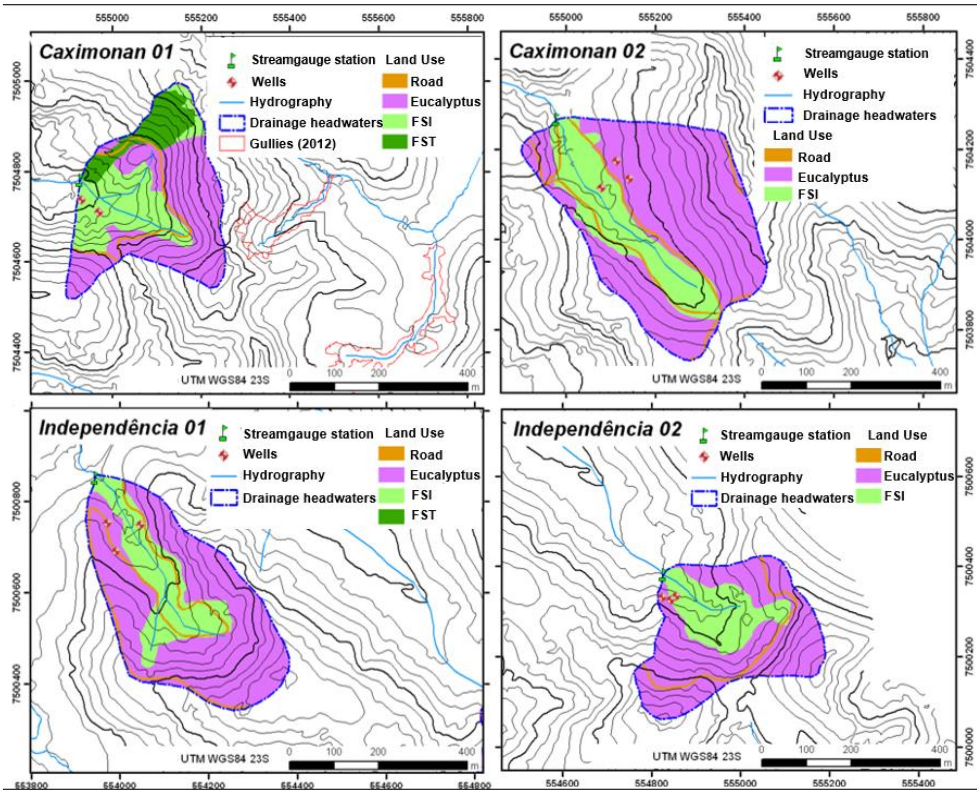

Figure 2. Use and coverage of the four drainage headwaters monitored with eucalyptus plantations on the Caximonan and Independência farms and the location of the wells. FSI: early secondary forest, FST: late secondary forest.

Table 1. Use and coverage characteristics and geomorphological parameters of the monitored headwaters.

Station	Use and Coverage									Geomorphological Parameters					
	Area	EUC		EST		FSI		FST		P	Cc	Dd	H	G	Ic
	(ha)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(m)	(m)	(m/ha)	(m)		(%)
Cax 01	10.7	5.4	50.1	0.5	4.3	3.3	31.3	1.5	14.3	1500	443	41.4	127	0.33	59.7
Cax 02	18.0	12.8	70.8	0.9	4.7	4.4	24.5	-	-	1712	513	28.5	107	0.17	77.2
Ind 01	14.0	9.8	69.6	0.8	5.9	3.4	24.5	-	-	1536	631	45.0	127	0.20	74.7
Ind 02	10.1	7.0	68.5	0.4	4.1	2.8	27.4	-	-	1316	197	19.5	126	0.31	73.6

EUC: eucalyptus; EST: unpaved roads; FSI: initial secondary forest; FST: late secondary forest; P: perimeter; Cc: channel length; Dd: drainage density; H: unevenness; G: basin gradient; Ic: roundness index.

Table 2. Structure parameters of eucalyptus plantations in drainage headwaters in January 2012.

Station	Esp. (m)	Planting date	Age (years)	DAP (cm)	H (m)	H_D (m)	AB (m^2/ha)	IMA (m^3/ha)	V (m^3/ha)
Cax 01	3 x 2	02/16/2004	7.95	14.1	23.1	28.2	28.9	40.4	321.2
Cax 02	3 x 1.5	02/16/2004	7.95	12.7	21.5	26.6	26.2	35.0	277.9
Ind 01	3 x 2	03/17/2004	7.85	14.8	24.0	29.4	28	40.7	319.8
Ind 02	3 x 2	03/17/2004	7.85	14.8	24.0	29.4	28	40.7	319.8

Esp.: Spacing between individuals; DAP: diameter at mean chest height; H: average height; HD: dominant height; AB: basal area; IMA: mean annual increment; V: volume of wood.

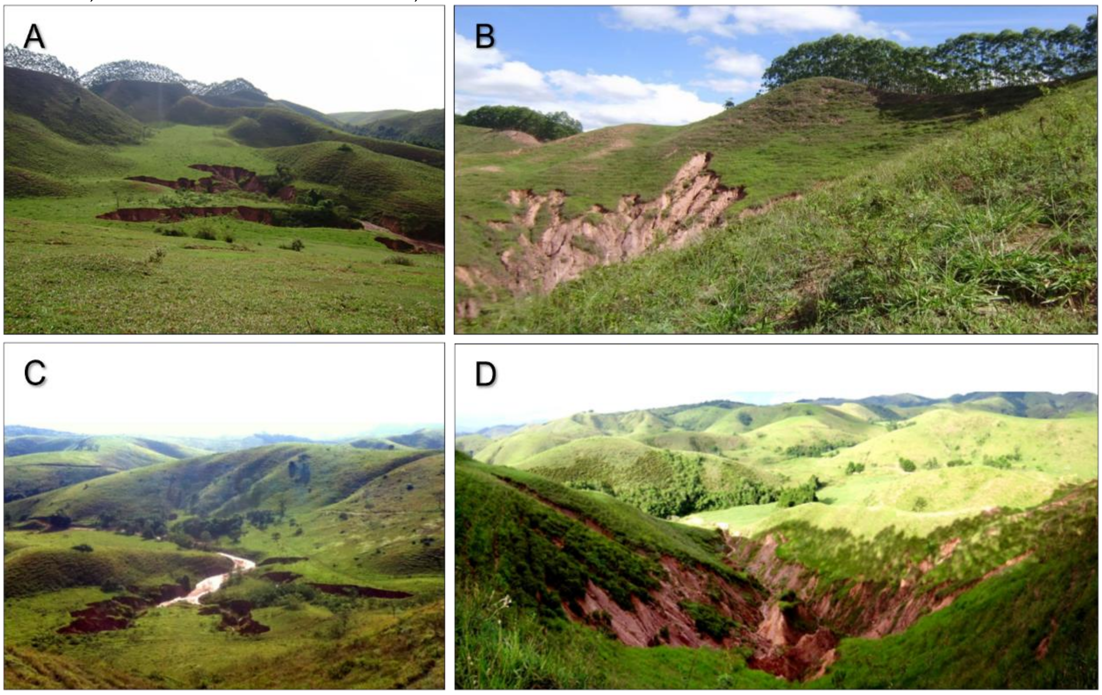

Figure 3. (A) Gully 01 (22° 33' 58.92" S / 44° 27' 35.41" W) at the valley bottom, at the Itamarati farm, with a view of the eucalyptus plantations in the drainage divider at the Caximonan farm (Cax 01); (B) Gully 02 (22° 33' 50.41" S / 44° 27' 42.86" W) at the Itamarati farm with a view of the eucalyptus plantations at the Caximonan farm; (C) Gully 01 with advancing digits at the bottom of the valley; (D) View from the divider of Gully 02 with the digits advancing towards the upper portion of the slope.

3. Materials and methods

To evaluate the hydrological and erosive responses to the introduction of patches of eucalyptus plantations in former pasture areas in the Sesmaria river basin, the following steps were carried out: (1) survey of local precipitation data; (2) infiltration experiments in eucalyptus plantation and pasture; (3) monitoring of suction in the unsaturated zone in drainage headwaters with gully channels and in eucalyptus plantations; (4) hydrological monitoring of the underground aquifer dynamics in drainage headwaters with eucalyptus plantations; (5) survey of gullies in the Sesmaria river basin before and after the introduction of eucalyptus plantations; and (6) assessment of sediment export from a gully during rainfall events. The summary of the data surveys is described in Table 3 and the sections below.

Table 3. Summary of the study's data collection.

Parameter	Period	Location
Precipitation	Oct/06 to Dec/16	Sesmaria Basin
Surface runoff	Dec/06 to May/07	Monte Alegre Farm
Infiltration capacity	Jan/14 to Feb/14	Itamarati and Caximonan Farms
Suction	Apr/15 to Nov/15	Itamarati and Caximonan Farms
Water table variation	Oct/09 to Mar/12	Caximonan and Independência Farms
Gully activity count and classification	2003 and 2012	Sesmaria Basin
Gullies activity classification	2004 to 2012	Itamarati Farm
Evolution of gully digits	Apr/12 to Jan/14	Itamarati Farm
Suspended sediment load	Jan/13	Itamarati Farm

3.1. Precipitation monitoring

Precipitation was measured at four points in the stations of the main rivers (Feio, Formoso, São João, Sesmaria) in addition to a point on the Monte Alegre farm and another point, more isolated, in the mountainous portion of the basin (Figure 1), totaling six points of measurement (primary data). The implementation of a rainfall monitoring point in the mountainous domain of this basin was carried out due to significant differences in the average annual rainfall between the stations located in the hilly domain and the mountainous domain (SATO, 2008). Secondary data from the station and HPP Funil Resende Aeroporto (ANA code 2244161) were also used to complement the rainfall records after March 2012 due to the discontinuity in rainfall monitoring, totaling seven monitoring points.

At Sesmaria, São João, Feio, Formoso, and Monte Alegre stations, rainfall measurements were taken using three handmade rain gauges, as replicas, with the arithmetic mean of these instruments being used as a reference value for daily rainfall. The handcrafted rain gauges were made with 100 mm diameter PVC pipes and placed on wooden supports; the precision and accuracy of these rain gauges were evaluated by Sato, Avelar, and Coelho Netto (2011). At Barra station, only a *Ville de Paris* rain gauge was used. Details of rainfall measurements at each station are described in Table 4.

Table 4. Characteristics of rainfall measurement stations.

#	Stations	Latitude	Longitude	Operator	Domain	Period	Interval
1	Sesmaria	22° 33′ 11,44″ S	44° 28′ 07,20″ W	This study	Hills	Nov/08 - Mar/12	Daily
2	São João	22° 34′ 01,15″ S	44° 28′ 26,37″ W	This study	Hills	Nov/08 - Mar/12	Daily
3	Feio	22° 34′ 52,44″ S	44° 29′ 11,21″ W	This study	Hills	Nov/08 - Mar/12	Daily
4	Formoso	22° 36′ 09,18″ S	44° 28′ 53,87″ W	This study	Hills	Nov/08 - Mar/12	Daily
5	Monte Alegre	22° 36′ 00,12″ S	44° 27′ 04,80″ W	This study	Hills	Oct/06 - Mar/12	Daily
6	Barra	22° 40′ 50,82″ S	44° 32′ 29,49″ W	This study	Mountain	Jun/09 - Mar/12	Daily
7	HPP Funil	22° 28′ 32,18″ S	44° 28′ 24,97″ W	FURNAS	Hills	Mar/12 - Dec/16	Daily

3.2. Infiltration in eucalyptus plantation and pasture

To determine infiltration and surface runoff, two Gerlach-type runoff plots, modified by Villas Boas et al. (2005) were installed and monitored. inside the eucalyptus plantation on the Monte Alegre farm (22° 36' 26.05″ S / 44° 27' 2.80″ W), one close to the divider (8° slope) and the other on the lateral slope (24° slope), as shown in Figure 4. These slope positions were selected because it is known that the divider is an infiltration area, usually with lower moisture content in the soil, while the lateral slope is a zone of water transfer to the lower portions and is generally more humid. It should be noted that the Monte Alegre farm is on the same lithology (metasediments of the Embu Complex, according to Eirado Silva, 2006) and geomorphological domain of convex-concave hills of the Caximonan and Independência stations. These plots cover an area of 90 m² each (9 x 10 m), with three columns and five rows of eucalyptus, totaling fifteen individuals each, and have a collecting trough in the terminal portion with a cover that conducts the water from the surface runoff to a 1,000 L covered water tank. The runoff readings were performed daily by a field reader using containers of known volume in the period from December 22, 2006, to May 31, 2007. The runoff volume data were converted into height by dividing the volume by the plot area and the relationship between runoff and precipitation was calculated for the same period based on the Monte Alegre rainfall station (Table 4).

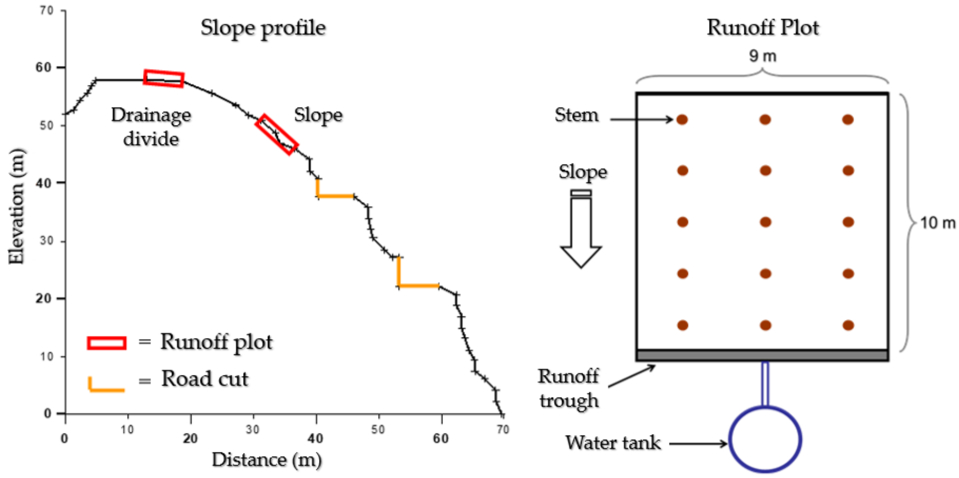

Figure 4. Location and detailing of surface runoff plots on the divider and the slope.

The estimate of soil infiltration capacity was obtained through tests with a double ring infiltrometer performed at the Cax 02 headwater drainage (22° 33' 54.01" S / 44° 27' 47.47" W) under eucalyptus cover, and on the Itamarati farm (22° 33' 51.83" S / 44° 27' 39.03" W), under pasture cover (**Figure 5**). The instantaneous infiltration capacity was calculated according to **Eq. (1)**. Nine field trials were carried out, five in pasture and four in eucalyptus plantation in the period from 01/30 to 02/01/2014. In calculating the basic infiltration rate (VIB) **Eq. (2)** by Horton (1939) was used, as worked by Kazay and Oliveira (2014):

$$I_t^{obs} = \frac{(h_1 - h_2)}{\Delta t} \quad (1)$$

where:

I_t^{obs} = infiltration capacity observed ($cm \cdot s^{-1}$)
h_1 = upper water level (cm)
h_2 = lower water level (cm)
Δt = time elapsed from the passage from h_1 to h_2 (s)

$$f = f_c + (f_o - f_c).e^{-\beta t} \quad (2)$$

where:

f = infiltration rate (cm/s)
f_c = infiltration rate in status of saturation (cm/s)
f_o = early infiltration rate (cm/s)
t = time (s)
β = parameter that should be determined as of field measurements (1/s)

3.3. Monitoring of suction in the unsaturated zone in drainage headwaters with gullies and eucalyptus plantations

Seeking to understand the behavior of water in the soil, at different depths in the unsaturated zone, three suction monitoring stations were installed in the field in the soil profiles, as follows: on a slope covered with eucalyptus (E); on a slope adjacent to the eucalyptus plantation and covered with *Brachiaria* grass/pasture (G1); on a slope covered with grass/pasture without interference from eucalyptus plantations (G2). The three stations were arranged in such a way as to keep the distance from the drainage divider and slope similar (Figure 5).

Monitoring was performed using granular matrix sensors from the manufacturer *Irrometer* (*Watermark* 200ss model) that work on the principle of variable electrical resistance. The data logger model 900M *Irrometer* was used to store data every 15 minutes, where eight sensors were coupled in-depth, seven suction sensors, and one for soil temperature. The depths of the suction sensors installed in the soil were: 20 cm, 50 cm, 80 cm, 120 cm, 150 cm, 200 cm, and 300 cm. Data from the three monitoring stations were obtained during the period from April 2015 to November 2015. The rainfall data used in the analyses were from the HPP Funil Resende Aeroporto station.

Field observations guided the choice of monitored depths, as well as previously developed studies that sought to compare different coverages, mainly between forested and pasture areas, such as Jansen (2001), Silveira (2004), Dias and Coelho Netto (2011) and Marques et al. (2018). In addition, it was observed that the grassroots (*Brachiaria*) root matrix were concentrated up to a depth of 40 cm, corroborating the survey carried out by Cambra and Coelho Netto (2000) in the neighboring basin (Bananal River). The selection of the smallest depths (20, 50, and 80 cm) for the installation of suction sensors sought to evaluate the entry of water into the soil. The choice of greater depths (120, 150, 200, and 300 cm) was linked to the eucalyptus pivoting root system, to analyze water percolation at greater depths.

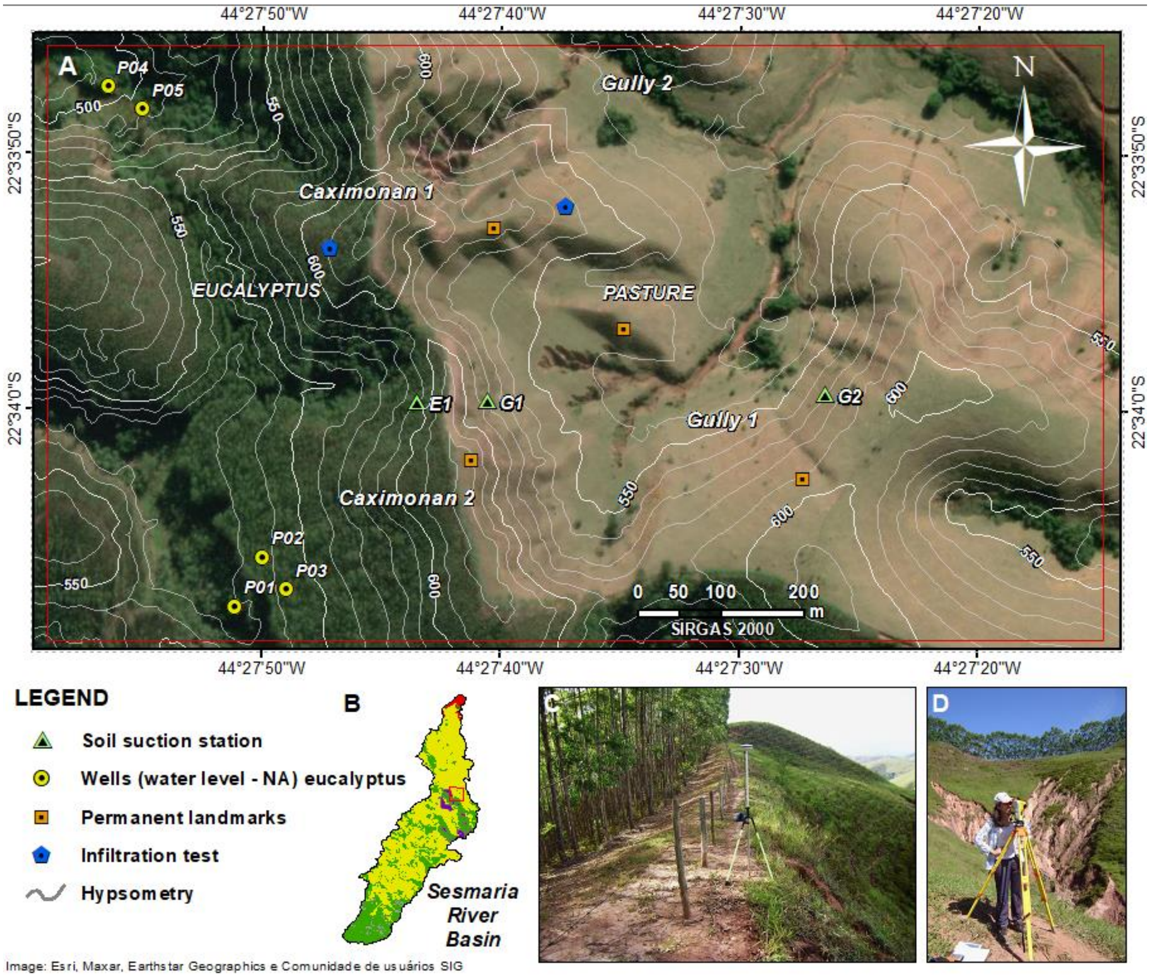

Figure 5. (A) Overview of the study monitoring area with eucalyptus plantation (Caximonan farm) and pasture (Itamarati farm) with the location of the network of landmarks for monitoring the evolution of gullies, wells and piezometers, and stations with suction monitoring of the soil. (B) Sesmaria River basin and, in red, highlight of the location of the monitoring area. (C) GNSS Trimble receiver for building the landmark network; (D) Survey of the perimeter of the gully using a total station from the landmark network.

3.4. Monitoring of underground water level (NA) in drainage headwaters with eucalyptus plantations and inside gullies

The four drainage headwaters highlighted in Figure 2 (Cax 01, Cax 02, Ind 01, and Ind 02) were monitored between 2009 and 2012 through the installation of wells to monitor groundwater associated with rainfall monitoring. The drainage headwaters are at a maximum distance of 4 km from each other and have similar geological substrate, dimensions, and axis orientation (Figure 2).

The water level (NA) variation was monitored in eleven wells installed in the four headwater drainage stations: Caximonan 01 (P4 and P5), Caximonan 02 (P1, P2, and P3), Independência 01 (P7, P8, and P9) and Independência 02 (P10, P11), as shown in Figure 2 and Table 5. All wells had water at some point in the monitoring period, except for P12, and for this reason, it was excluded from the analyses.

Table 5. Location and characteristics of groundwater monitoring wells.

Wells	Station	Latitude	Longitude	H (m)	Depth (m)	Position	Coverage
P01	Cax 02	22º 34′ 7,657″ S	44º 27′ 51,199″ W	527.75	8.8	FV	Capoeira vegetation
P02	Cax 02	22º 34′ 5,740″ S	44º 27′ 50,045″ W	538.87	19.0	BME	Eucalyptus
P03	Cax 02	22º 34′ 6,989″ S	44º 27′ 49,028″ W	544.20	17.5	BME	Eucalyptus
P04	Cax 01	22º 33′ 47,434″ S	44º 27′ 56,519″ W	494.82	5.8	FV	Grass
P05	Cax 01	22º 33′ 48,311″ S	44º 27′ 55,129″ W	510.03	12.0	BME	Grass
P07	Ind 01	22º 35′ 57,201″ S	44º 28′ 26,982″ W	480.49	4.5	FV	Capoeira vegetation
P08	Ind 01	22º 35′ 57,119″ S	44º 28′ 29,591″ W	485.46	14.5	BME	Eucalyptus
P09	Ind 01	22º 35′ 59,117″ S	44º 28′ 28,926″ W	487.10	14.8	BME	Eucalyptus
P10	Ind 02	22º 36′ 10,606″ S	44º 27′ 58,583″ W	525.78	6.5	FV	Grass
P11	Ind 02	22º 36′ 10,906″ S	44º 27′ 59,023″ W	536.08	16.2	BME	Eucalyptus
P12	Ind 02	22º 36′ 10,720″ S	44º 27′ 59,701″ W	542.46	18.2	BME	Eucalyptus

FV: valley bottom, BME: low-medium slope, H: well elevation.

The NA depth reading was performed weekly using a manual sensor. The NA data were worked as depth concerning the surface, as elevation from the geoidal elevation data and were normalized to compare the recharge and depletion responses between the different wells, according to Eq. (3). In each drainage headwater with eucalyptus plantations, a well was installed inside the Permanent Preservation Area (APP), close to the drainage channel, while the other wells were installed inside eucalyptus plantations, aiming to monitor the water table oscillation in valley bottoms and low-medium slope. The rainfall data used in the analysis were the average of the stations inserted in the Sesmaria River basin.

$$\widetilde{NA}_{i,j} = \frac{NA_{i,j} - \overline{NA}_i}{DP_i} \quad (3)$$

where:

$\widetilde{NA}_{i,j} =$ i well normalized NA depth on j day

$NA_{i,j} =$ i well NA depth on j day

$\overline{NA}_i =$ average NA depth of i well data set

$DP_i =$ NA depth standard deviation of i well data set

3.5. Survey of gullies in the Sesmaria river basin before and after the introduction of eucalyptus plantations

To survey the total number of gullies present in the Sesmaria river basin before and after the introduction of eucalyptus, two orbital images were selected in two periods: in 2003 (*Ikonos – Google Earth/ Maxar Technologies*) and in 2012 (*QuickBird* / Sesmaria Project). The gullies were classified as active and inactive in the two periods analyzed through the interpretation of satellite images, to investigate possible changes in the activity of the gullies present in the basin. It is important to point out that the introduction of plantations along the basin took place in 2004, therefore the images refer to the moment before and after the introduction of eucalyptus monoculture in the area.

The evolution of the two gullies on the Itamarati farm, located on the opposite side of the eucalyptus plantations on the Caximonan farm, was analyzed from 2004 to 2023. For the temporal analysis of the evolution of the two gullies, aerial photographs, and orbital images were analyzed to obtain a history with different stages of development, thus having an overview of the moments of activity and stability of these processes. IBGE aerial photographs 2743-1 NO and 2743-1 SO, relative to the years 2004, served to assess the stage of the two gullies in the year of introduction of eucalyptus plantations in the area. High-resolution spatial orbital images owned by *Maxar Technologies* through *Google Earth Pro* dated 02/07/2003, 08/21/2010, 05/03/2016, and 06/09/2023 were used for the analysis of the evolution of the gullies.

To estimate the retreat rates of the digits heads of the gullies, surveys were carried out in the field, using as a basis a network of permanent and temporary landmarks with the aid of D-GPS *Trimble* model R6 and total station *Trimble* model S3. The entire digital base was structured in the field by transposing the geodesic landmark SAT 93652 of the city of Bananal/SP to control points around the gullies, totaling four permanent landmarks in concrete and nineteen temporary landmarks, georeferenced with GNSS receivers through the static relative positioning technique. The total station was positioned on the network of permanent and temporary landmarks and, for greater precision in the contour of the gullies, the prisms were positioned every 2 m, closing a polygon for each gully. The perimeter of Gully 01 was outlined at different times: April 2012; January 2013, August 2013, and January 2014. From the overlapping of these contours in the ArcGIS 10 software, the difference in the areas of the digits and the retreat rate of the head of the digit channel were calculated.

Based on the comparison of aerial photographs with orbital images, as well as the survey and observations made in the field, it was possible to obtain a history of the evolution of the gullies, in the pre-planting phase (before 2004) and after their introduction, concerning periods of activity/stability and development.

4. Results

4.1. Behavior of water in the soil

4.1.1 Production of surface runoff on slopes with eucalyptus plantations and grass

Surface runoff was monitored on 52 rainy days, from December 2006 to May 2007, indicating an average value of the Q/P ratio (surface runoff flow/terminal precipitation) varying between 0.1% at the divider and 0.2% on the lateral slope, where maximum values reached only 1.3% and 3.8%, respectively, in response to 90 mm precipitation. The slope on the lateral slope (24°) is three times greater than that of the divider (8°), which seems to influence these differences in the Q/P ratio. It is worth mentioning that the plantations follow a uniform spatial pattern and have a thick layer of unstructured plant litter (up to 50 cm thick) with a moisture retention capacity similar to that observed in humid tropical forests, around 250% (COELHO NETTO, 1985; MIRANDA, 1992). This low proportion of surface runoff suggests, on the other hand, that these plantations favor the entry of terminal precipitation, more concentrated near the trunks (SATO et al., 2011), and their pivoting roots (~ 2 meters deep) contribute to the preferential percolation in-depth, as observed by Silveira et al. (2005) through field experiments on the slopes of the Tijuca National Park, in Rio de Janeiro. In this way, the slopes under these eucalyptus plantations constitute a favorable environment for the infiltration of rainwater.

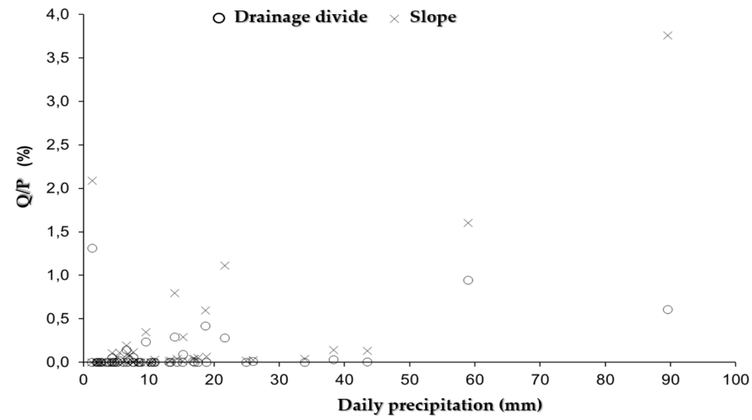

Figure 6. Variation of the Q/P ratio (surface runoff/precipitation) as a function of precipitation at the Monte Alegre station in the divider and slope plots.

For purposes of comparison with the past environment of grasses with extensive pasture, Table 6 shows the results of measurements of basic infiltration speed (VIB) of trials with double ring infiltrometers. Trials carried out on pasture (Itamarati farm) and eucalyptus plantation (Caximonan farm) lasted from 69 to 262 minutes, depending on the specific characteristics of the trial points. It is observed that the average VIB varies between the soil planted with eucalyptus (1.01x10^{-2} cm/s) and pasture (6.67x10^{-3} mm/s), corroborating the results of the runoff plots that present the eucalyptus plantations as an environment with greater infiltration capacity than in the pasture environment.

Table 6. Basic infiltration rate (VIB) in infiltration capacity trials in pasture and eucalyptus.

Treatment	Pasture		Eucalyptus	
Trials #	Duration (min)	VIB (cm/s)	Duration (min)	VIB (cm/s)
1	262	2.25x10^{-3}	69	2.08 x10^{-2}
2	102	6.73x10^{-3}	174	5.53 x10^{-3}
3	130	7.27 x10^{-3}	163	4.00 x10^{-3}
4	145	7.31 x10^{-3}	---	---
5	74	9.80 x10^{-3}	---	---
Average	143	6.67 x10^{-3}	135	1.01 x10^{-2}
Deviation	72	2.74 x10^{-3}	58	9.31 x10^{-3}

4.1.2. Suction variation in eucalyptus plantations and grass/extensive pasture

Figure 7 presents the mean suction values at the three depth monitoring stations (20 cm, 50 cm, 80 cm, 120 cm, 150 cm, 200 cm, and 300 cm). The time series from April to November 2015 showed two windows without data (from mid-May to early June and from late July to September) due to equipment failures. In the eucalyptus (E) station, the mean suction values were higher at all depths, if compared to the other stations, highlighting a significant reduction in suction values at 150 cm depth, that is, at the height of the lower limit of the eucalyptus pivoting roots, suggesting soil water extraction by eucalyptus. On the slopes under grasses, on the other hand, a differentiated behavior can be noticed between sites G1 (adjacent to the eucalyptus plantation) and G2 (without the influence of these plantations). In the first, the average suction value at the top of the soil (20 cm/depth) is lower (~ -80 kPa) and with a wide standard deviation (between -15 and -145 kPa) in an approximation to the average values observed in the soil with eucalyptus (~ -125 kPa), but higher than the G2 site, where average values and deviations are lower than -75 kPa and more uniform in depth, indicating greater moisture storage.

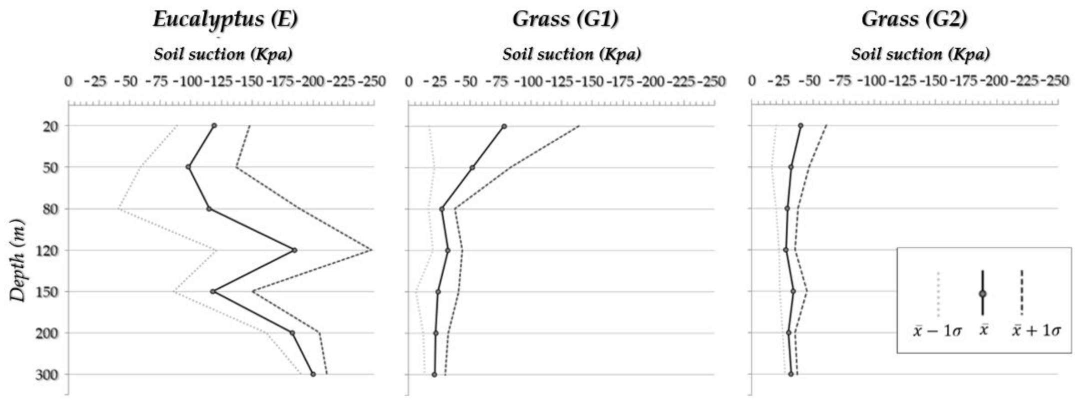

Figure 7. Average suction with standard deviation per depth at the eucalyptus (E), grass 1 (G1), and grass 2 (G2) stations.

The daily suction variations can be seen in Figure 8, in a period of the beginning of the rainy season (between October 2nd and November 15th, 2015) that followed a long drought, in the three stations monitored. Although this sampling time is short, the data reflect a representative behavior of drier periods.

In the soil profile with eucalyptus, there was a delay in the responses to rainfall inputs at all depths, except at 150 cm where the suction values, which had been maintained at around -150 kPa during the previous drought and next to the values of the upper portion of the soil (at 20 and 50 cm/depth), showed an abrupt drop right at the beginning of the rains. This behavior reveals a rapid entry of water into the soil, possibly close to the pivoting roots of the eucalyptus. Soon after this rapid wetting at a depth of 150 cm, a gradual increase in suction was observed in the following week, indicating water loss. Possibly this is associated with capillarity in the surrounding soil matrix, followed by a period of stability, despite successive daily rains. After an accumulated total of rainfall, around 140 mm, the suction at 150 cm depth alternated with approximate values between -70 and -20 kPa. At shallower depths, at the top of the soil (20 cm), the suction varied little during the entire period; the moisture front in the soil matrix only reached depths between 50, 80, and 120 cm around 3 to 4 days after the end of the rains, but did not reach depths greater than 200 and 300 cm.

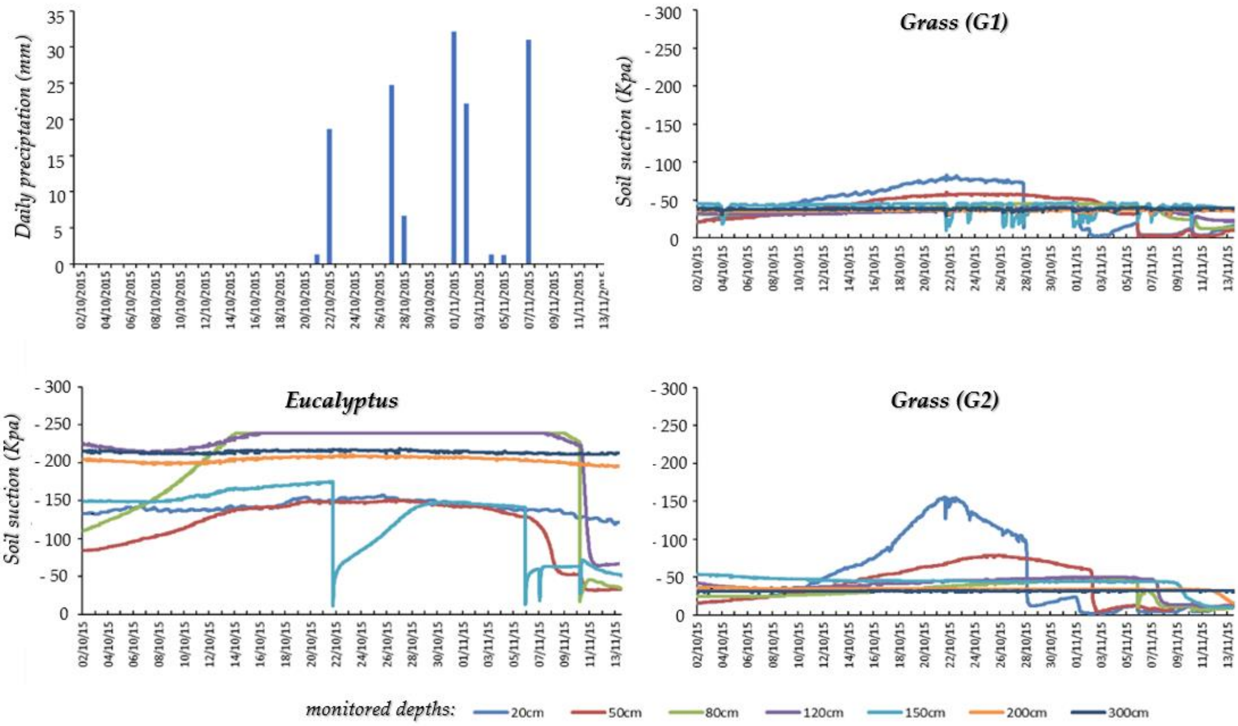

Figure 8. Precipitation at Resende station and suction (kPa) per depth at Eucalyptus (E), Grass 1 (G1), and Grass 2 (G2) stations from October to November 2015.

In the grass/pasture stations (G1 and G2) all suction values were low in the period before the rains, progressively increasing at depths of 20 and 50 cm until the onset of rains and reaching -80 kPa at the top of the soil in G1, reaching just over -150 kPa at the same depth as the G2 site. At a depth of 50 cm, small differences also occur in the behavior of suction, highlighting again a relatively greater amplitude of variation in G2 than in G1. This fact suggests that the G2 slope tends to be less humid than in G1, at least in the upper half meter of the soil (**Figure 8**). Strengthening this observation, it is noted, in the same figure, that at the end of the rainy season the upper half meter reaches saturation before the end of the rainy season and, shortly after, the depths of 80 and 120 cm also reach saturation. In G2, similar behavior is observed in the half meter above the soil, but with a greater range of variation; at this site, the moisture front advanced to a depth of 200 cm with a greater delay than the shallower depths, as expected.

4.1.3. Rainfall-groundwater level (NA) ratio in headwater drainage valleys with eucalyptus plantations

Water levels (NA) vary between monitored headwater valleys, especially between valley bottom (FV) and low-medium slope (BME) positions – see Figure 9 and Table 7. Wells at the bottom of valleys (P1, P4, P7, and P10) have water levels closer to the surface, as expected by the convergence of flows from the higher parts of the surroundings. The NA closest to the land surface occurs at the bottom of the valley at P4 (-1.90 m) and at P7 (-3.36 m) with maximum values of -0.10 m and -2.34 m respectively, as well as have the highest coefficients of variation (CV= 38.7% and CV= 19.1%, respectively). The NA in P4 is closest to the land surface and presents the greatest oscillations, reflecting the balance of water inputs and losses in the direct contribution area with eucalyptus plantations and also the grass matrix surrounding this small valley. The behavior of the relatively more stable NA at P1 may reflect the delay in recharge at greater depths, as expressed by the suction behavior previously mentioned. Another aspect to be highlighted in the same Figure 9 and Table 7 refers to the deepest values of NA in wells P2 and P3 with average values of -16.29 m (CV=2.6%) and -16.35 m (CV=3.7%), respectively, both located on the low-medium slope of rectilinear geometry. The other wells have an average intermediate NA between -8.64 m (P5), -11.39 m (P8), and -13.07 m (P9), emphasizing that P5 is located on the low-medium slope, but closer to the valley bottom, while P8 and P9 are further away on the middle slope.

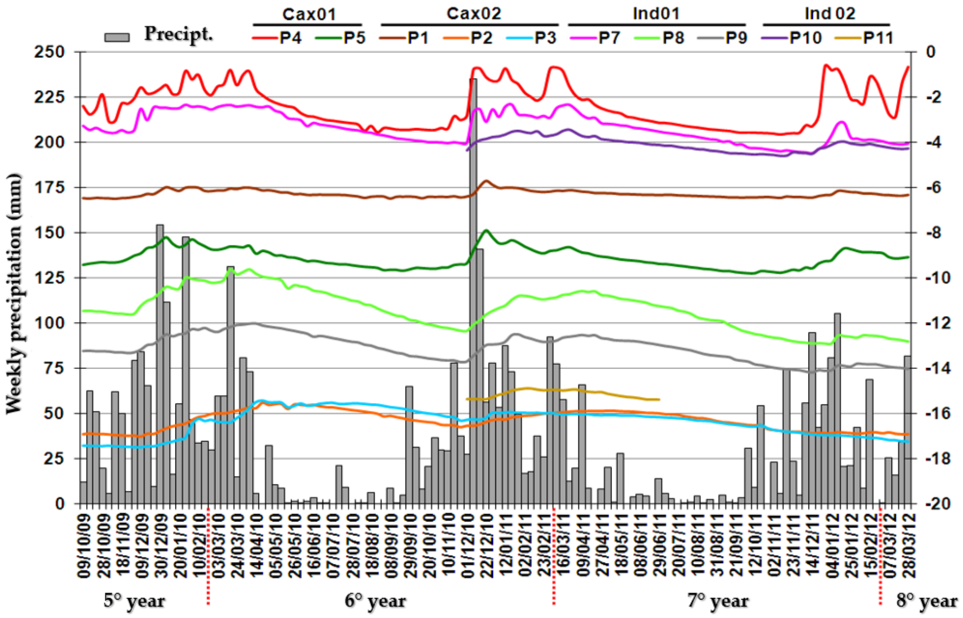

Figure 9. NA depth oscillation in all stations in drainage headwaters with eucalyptus plantations. The x-axis (time) also shows the age of the eucalyptus plantations, in red.

Table 7. Elevation of wells and NA depth per station.

Parameters	**Cax 01**		**Cax 02**			**Ind 01**			**Ind 02**	
	P4	**P5**	**P1**	**P2**	**P3**	**P7**	**P8**	**P9**	**P10**	**P11**
Elevation (m)	494.82	510.03	527.74	538.87	544.20	480.49	485.46	487.10	525.78	536.08
Position	FV	BME	FV	BME	BME	FV	BME	BME	FV	BME
NA $_{AVER}$ (m)	-1.90	-8.64	-6.27	-16.29	-16.35	-3.36	-11.39	-13.07	-4.08	-15.13
NA $_{MAX}$ (m)	-0.10	-7.39	-5.71	-15.52	-15.42	-2.34	-9.62	-11.99	-3.44	-14.89
NA $_{MIN}$ (m)	-3.13	-9.31	-6.48	-17.01	-17.48	-4.48	-12.90	-14.16	-4.58	-15.39
Δ NA (m)	-3.03	-1.92	-0.77	-1.49	-2.06	-2.14	-3.28	-2.17	-1.14	-0.50
DP (m)	0.9	0.4	0.2	0.4	0.6	0.6	0.9	0.6	0.3	0.2
CV (%)	38.7	4.8	2.4	2.6	3.7	19.1	7.9	4.6	7.9	1.2

FV: valley bottom; BME: low-medium slope

In all years there was a reversal of the downward trend in the NA from December onwards, and the duration of this rise in the NA varied between years. This reversal is simultaneous in all wells, regardless of depth and elevation, which suggests regionally controlled groundwater dynamics. The increase in NA is later reversed, with a new period of slow and gradual decline taking effect (Figure 10). The behavior of the NA lowering contrasts with that of the rise, the latter being more accentuated and shorter.

A different behavior in the general rise of the NA occurred in the period 2011-2012, in which the positive oscillations were markedly smaller than in the years 2009-2010 and 2010-2011. This difference is due to the lower accumulated rainfall in the period from September to March (rainy period) of 2011-2012 compared to the same period of 2009-2010 and 2010-2011. In the period from September 2011 to March 2012, there were also fewer rainy days. It is relevant to note that in the same period, recharge was less pronounced in all wells, while in wells P2 and P3, the downward trend was not even broken, despite showing a reduction in the drop.

The aquifer recharge, or saturated zone, was strongly related to the accumulated rainfall in 120 days (**Figure 11**), especially for the wettest periods of 2009-2010 ($R^2 = 0.93$) and 2010-2011 ($R^2 = 0.92$). The analysis of the data series from December 2011 to March 2012 indicates an $R^2 = 0.20$, since the lowest accumulated precipitation in 120 days compared to previous years and less than 800 mm did not support the increase in the NA, which began to decline prematurely from January 2012 and more abruptly than in previous years.

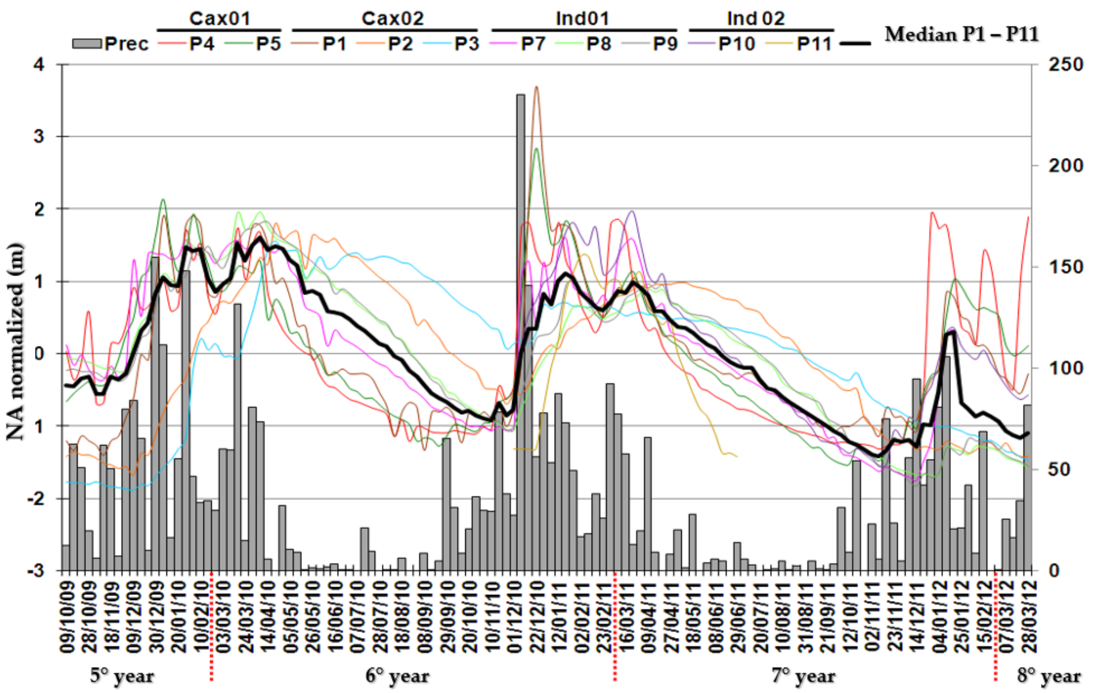

Figure 10. Normalized NA depth oscillation at all stations with median indication. The age of the eucalyptus plantations is also indicated on the x (time) axis.

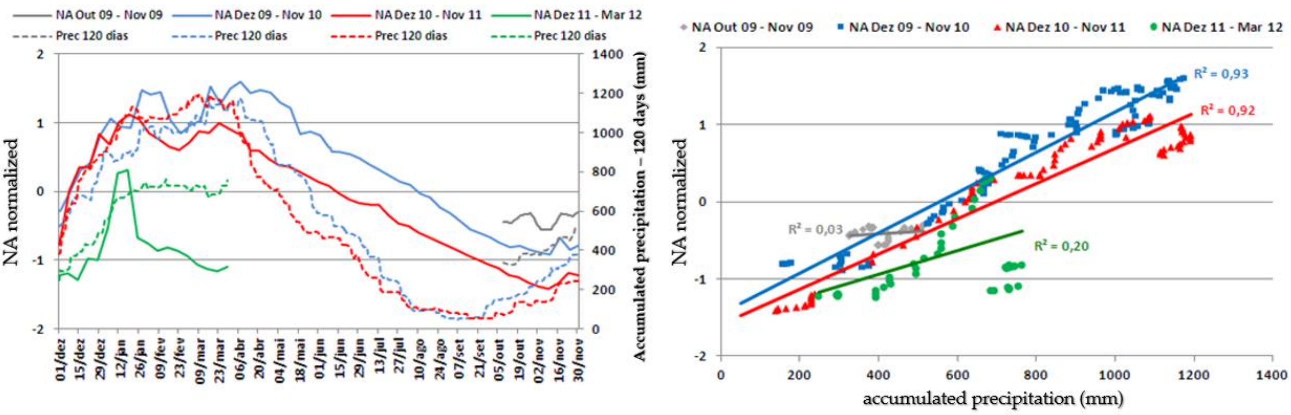

Figure 11. (A) Normalized NA median variation (P1 to P11) and 120-day accumulated precipitation. (B) Correlation between NA and 120-day accumulated precipitation in different periods.

Just as the accumulated precipitation in the rainy season is relevant for understanding NA oscillations, higher volume rainfall also plays a fundamental role in aquifer recharge. This recharge is detected quite quickly in the valley bottoms where the NA depth is smaller. As an example, in P4 an elevation of the NA greater than 2 m was detected and, in P7, it was greater than 1 m in the week of 12/08/2010 in which the accumulated was 235 mm (Table 8). This week saw the highest rise during monitoring and other weeks with high precipitation values also provided significant positive variations in the NA. Once again, the NA oscillations in the wells at Cax 02 and Ind 02 stations were smaller than at Cax 01 and Ind 01 stations. It means, therefore, that the depths of the NA vary spatially between the headwater valleys, but also over time, that is, the rainfall distribution regime at regional and local levels.

Table 8. Weekly NA variation of the wells (m) for weekly precipitations greater than 100 mm.

Date	Weekly Precipitation	Cax 01		Cax 02			Ind 01			Ind 02	
		P4	P5	P1	P2	P3	P7	P8	P9	P10	P11
12/30/2009	154 mm	0.17	0.22	0.15	0.13	0.07	0.00	0.25	0.22	ND	ND
01/06/2010	111 mm	0.17	0.22	0.15	0.13	0.08	0.00	0.25	0.22	ND	ND
01/27/2010	148 mm	0.96	0.11	0.14	0.06	0.09	0.15	0.49	0.04	ND	ND
03/17/2010	131 mm	0.62	0.09	0.08	0.06	-0.02	0.02	0.47	0.09	ND	ND
12/08/2010	235 mm	2.03	0.57	0.10	0.00	0.03	1.34	0.27	0.25	0.29	ND
12/15/2010	141 mm	0.06	0.52	0.33	0.06	-0.03	0.14	0.20	0.24	0.15	ND
01/11/2012	106 mm	0.04	0.32	0.16	0.05	0.01	0.51	0.35	0.21	0.12	ND

N.D.: no data. Note: P11 had no data because it had a smaller historical series that did not coincide with precipitation events greater than 100 mm.

4.2. Erosive behavior and evolution of gullies

4.2.1 Erosive reactivation in gullies after planting eucalyptus

The identification and classification of the erosive activity of the gullies carried out based on a satellite image from the year 2003 (before the eucalyptus plantations), showed the occurrence of 29 gullies in the headwater valleys, connected to the regional network of channels, among which 17 (58.62%) were stabilized; 9 (31%) were partially stable, with erosive activity and only 3 (10.34%) remained active in the Sesmaria River basin. A second survey carried out using high-resolution images for the years 2010 and 2011, respectively after 5 and 6 years of eucalyptus plantations in the basin, indicated that, among these same 29 gullies mapped in 2003, only 13 (44.83%) remained stable; among the 9 gullies that were partially active in 2003, 2 (6.8%) gullies were fully activated, one of them adjacent to the eucalyptus plantation. In this period after planting, active gullies went from 3 to 9 (31%) cases of reactivation.

Two characteristic cases of reactivation of (previously stabilized) gullies and intensification of erosion in partially active gullies correspond to gullies 01 and 02, both located on the Itamarati farm and adjacent to the eucalyptus plantations on the Caximonan farm. Erosive work was monitored by comparing orbital images and aerial orthophotos, along with field measurements of their respective perimeters between 2012 and 2014, to assess growth rates. It is noteworthy that these gullies grew regressively across valley bottoms, in connection with the expansion of the regional channel network, stabilizing in an environment dominated by grasses with extensive pasture until the year 2004 (Figure 12); the presence of arboreal vegetation inside the incised channel of these gullies testifies to the condition of stability of the erosive activity, whose reactivation occurred soon after the eucalyptus plantations in mid-2004 in the valleys of adjacent headwaters. It should be noted, however, that some erosive activity still occurred in Gully 02, which already reached the steepest portion of the lower slope before the planting of eucalyptus on the Caximonan farm. In the same Figure 12, it can also be seen that the incision at the head of the erosion channel of gully 1 was stabilized along the erosion channel and in the small digit channels that already spread out at the bottom of the valley, accompanying its enlargement in the form of an amphitheater. In this position, the channel incision evolved into a thick deposit of sediments (colluvium and alluvium-colluvium) possibly of Holocene age, like other similar deposits dated in the neighboring basin of the Bananal River (COELHO NETTO, 1999). It is worth mentioning that the bifurcations of the channel network, as well as the changes in the orientation of the channels of the two gullies, result from the intersection of sub-vertical fractures through which the underground artesian flows emerge that lead to the incision of the erosive channel, as well as the evolution of the channel network, as studied in detail in the Bananal river basin. (COELHO NETTO; AVELAR, 1992; LEAL; COELHO NETTO; AVELAR, 2015; FONSECA et al., 2006).

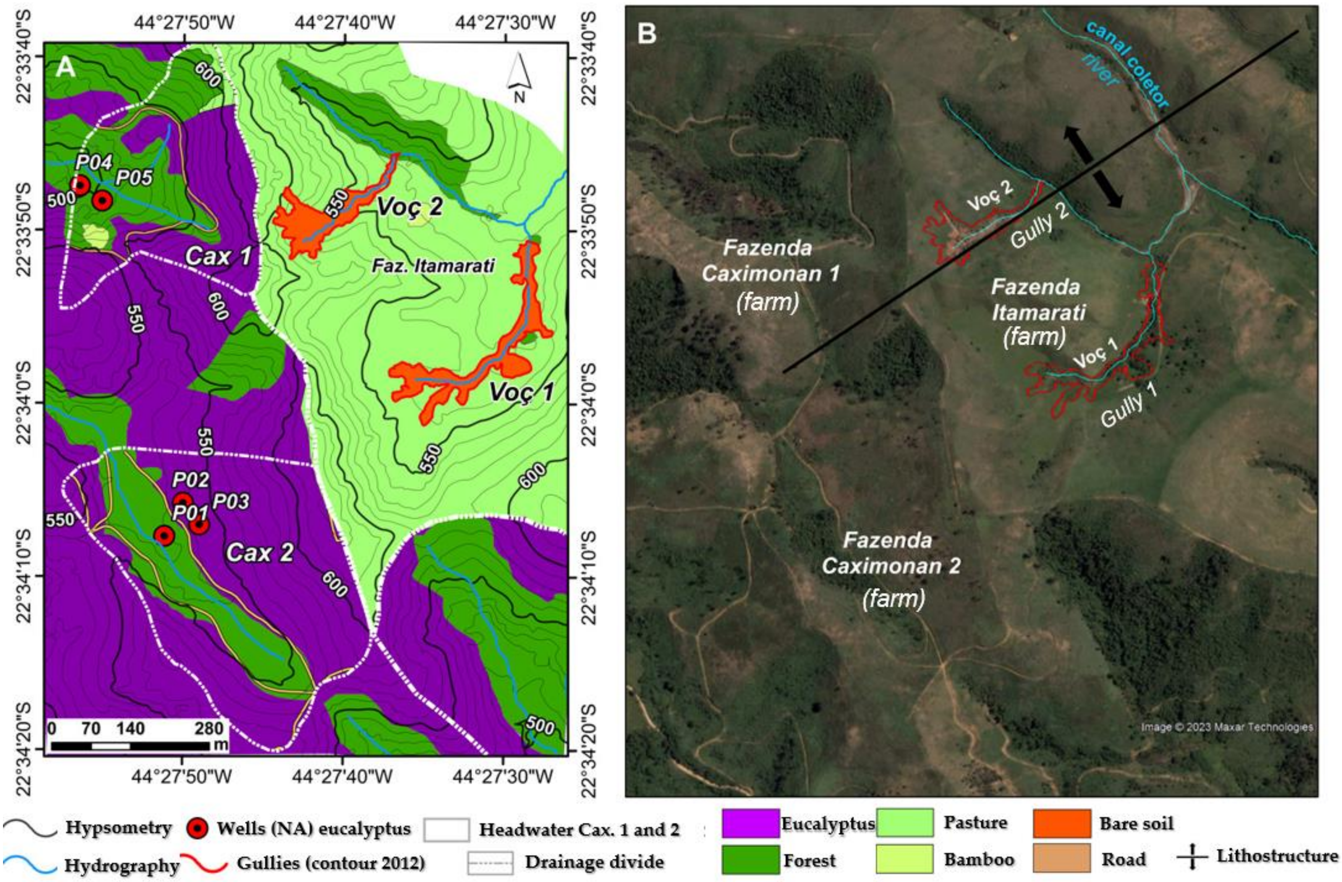

Figure 12. Left - Topographic map and vegetation cover on the Caximonan farms (to the left of the main watershed) and on the Itamarati farm (pasture); emphasis on eucalyptus planting sub-basins and monitoring of subsurface waters (Cax 1 and Cax 2); gullies 1 and 2, in red, show the 2012 cut. Right - Photo image of the same area in 2003, before eucalyptus planting (2004), highlighting gullies 01 and 02 in the extension of the channel network; arboreal vegetation at the bottom of erosive channels indicates stability; the outline in red depicts the year 2012. The arrows and the black line indicate the axis of an underlying anticline.

On Figure 12 yet, it can be seen that the erosive activity in gully 02 approaches the watershed with the headwater valley Cax 1, fanning out on the low-medium slope and thus leading to the retreat and widening of the valley headwaters; on the lateral edges of the incised channel, erosion reaches the lower slope, in a process of valley floor enlarging. Gully 01, in turn, is located on the opposite side of the two headwater valleys with eucalyptus plantations (Cax 1 and Cax 2), prevailing a breakdown of linear erosion in channel digits with the opening of the valley bottom in the form of an amphitheater at a more advanced evolutionary stage than at the gully 02 headwater.

Figure 13 allows a more detailed view of the two gullies focused on in this study, highlighting their morphological features at different times: before the eucalyptus plantations (2003) and after the plantations on the Caximonan farm, in 2010; the red line refers to the contour of the gully in the first year of monitoring (2012). It can be seen from these images that the retreat of Gully 02 between 2010 and 2012 was relatively short, having been more effective in the first years after planting eucalyptus. However, in that same period, the retreat of Gully 01 was more pronounced, as attested by the respective erosion rates that will be seen below. In both cases, in the same period, the erosive activity was more restricted on the edges of the incised channels where the siltation of the excessive load of sediments from the erosive activity upstream prevailed.

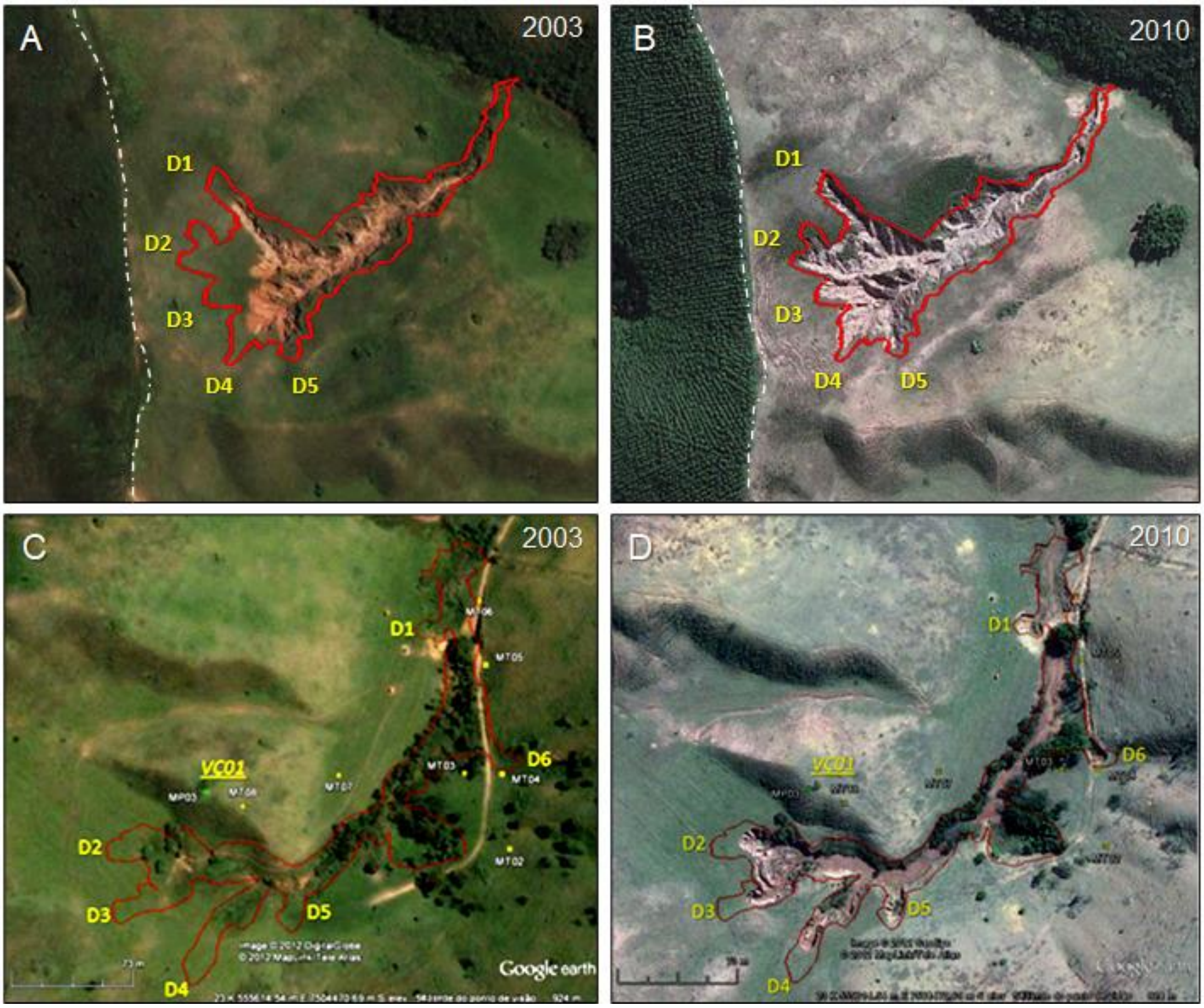

Figure 13. Gullies 01 and 02 at different times: A- Gully 02 before planting eucalyptus in the adjacent headwater valley (2004); B- Image of gully 02 in the year 2010; C- Gully 01 before planting eucalyptus in the two adjacent headwater valleys (2004); D- Gully 01 in the year 2010. The contour lines in red show the outline of the gullies in the year 2012 and the yellow, the digits of the gullies. Satellite imagery credit: *Google Earth Pro / Maxar Technologies*.

4.2.2 Mechanisms of erosion and regressive growth of gullies

Inside gullies 01 and 02, it was observed, in the field, that the exfiltration of groundwater occurs throughout the year at the bottom of the incised channels, sustaining a permanent water flow even in periods of drought or low rainfall, confirming, in both cases, the contribution of the permanent aquifer that is fed by regionally distributed rainfall. In addition to the continuous exfiltration of groundwater at the bottom of the erosive channel, the occurrence of temporary exfiltration in the unsaturated soil zone was also observed, both on the edges of the incised channels of gullies 01 and 02, as well as on the low-medium slope of the gully 02 head, in both cases fed by the local rainfall regime.

Figure 14 shows in detail the upper portion of gully 01 (Figure 14A) whose contribution area is adjacent to the eucalyptus plantations of the Caximonan farm, being able to capture underground water flows from this neighboring area, increasing the flow of water on the exfiltration faces of the inner edges of the digit channels and at the bottom of the gully channel. It is worth noting in Figure 14B that, at least between 2012 and 2014, erosive activity concentrated in the digit channels D2, D3, and D4, whose heads grow regressively towards the eucalyptus plantations, while D1 and D5 remain stable, suggesting a restriction in the reach of the water flows from the upstream contribution area. The total eroded area in digits D2, D3, and D4, in these two years, was 748.8 m² and the total retreat of the three-digit channels reached 37.34 m. Field evidence indicates that the erosive work driving the evolution of gully 01 results primarily from excess pore pressure on the groundwater exfiltration faces, driving seepage erosion as studied in detail in the Bananal River basin (COELHO NETTO, 2003; ROCHA-LEÃO et al., 2005; COELHO NETTO; FERNANDES, 1990). This mechanism favors the formation of piping whose internal growth leads to the formation of erosive tunnels which, reaching a certain size, cause the collapse of the overlying material. Figures 14 C and 14 D show the occurrence of morphological features of erosion tunnels and collapsed materials, also showing the contribution of temporary flows during rainy periods.

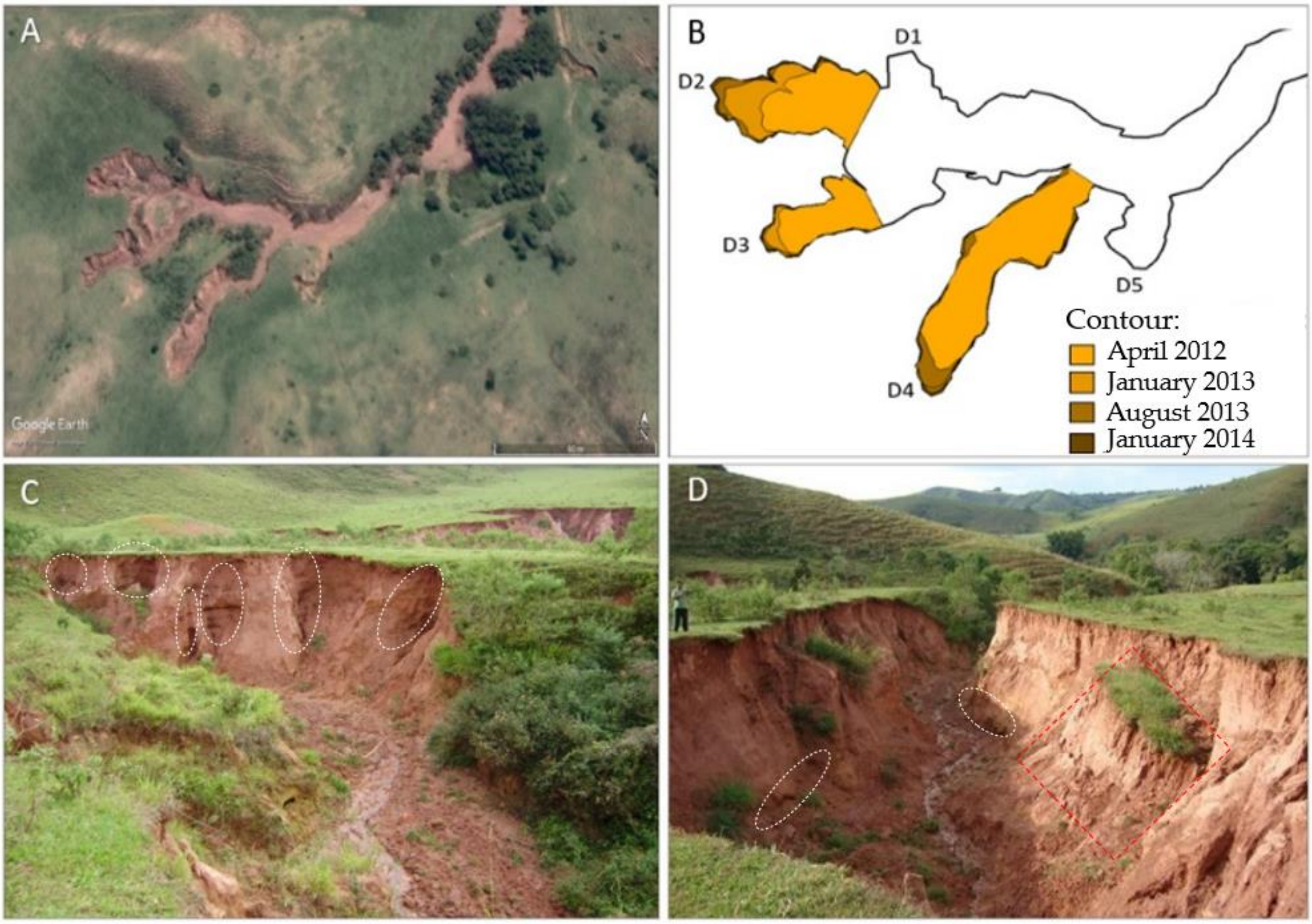

Figure 14. Erosive activity in gully 01 of the Itamarati farm: A- Photo-image of the upper portion of the erosive channel and the digit channels; B-Changes in the contour of gully 1 between the years 2010-2012; C- Head of channel-digit 4 highlighting the erosive tunnels (white dashed line) in the unsaturated zone and, D- View from upstream to downstream of gully 1 showing the erosive tunnels along the lower edge of the channel (white dashed line) and the collapsed material (dashed red rectangle).

In Table 9 one can see that the growth rate in the area, in the total period (2012 to 2014) was higher in channel-digit D2 (19.2 m^2/month), followed by D4 (11.1 m^2/month) and smaller in D3 (4.2 m^2/month), which presented an average retreat rate of 0.92 m/month, 0.52 m/month and 0.31 m/month, respectively. It is worth noting that during this sample period, erosion rates decreased by three digits; in the last two periods, D3 maintained low values and close to each other. Observing the histogram of monthly rainfall seen in Figure 15, the first monitoring period had the highest erosion rates despite the lower volume of accumulated rainfall, compared to the following rainiest periods. This fact suggests, once again, an additional contribution of water flows, possibly by *piracy of groundwater* from the adjacent headwater valley, with eucalyptus plantation, in the Caximonan farm, as seen and physically modeled in the Bananal River basin (LEAL; COELHO NETTO; AVELAR, 2015).

Table 9. Estimate of the rate of evolution of the active digits of gully 01.

Digits	Period (months)	Interval (days)	Growth of the area (m^2)	Rate in area (m^2/month)	Digit head retreat (m)	Digit head retreat rate (m/month)
D2	Apr/12 to Jan/13	275	295.1	32.2	14.9	1.63
	Jan/13 to Aug/13	212	84.8	12.0	3.7	0.53
	Aug/13 to Jan/14	152	42.3	8.3	1.1	0.22
	Total digit 2	639	422.2	19.2	19.7	0.92
D3	Apr/12 to Jan/13	275	56.0	6.1	5.60	0.61
	Jan/13 to Aug/13	212	19.1	2.7	0.49	0.07
	Aug/13 to Jan/14	152	14.6	2.9	0.47	0.09
	Total digit 3	639	89.7	4.2	6.56	0.31
D4	Apr/12 to Jan/13	275	147.9	16.1	8.05	0.88
	Jan/13 to Aug/13	212	72.5	10.3	1.61	0.23
	Aug/13 to Jan/14	152	16.5	3.3	1.42	0.28
	Total digit 4	639	236.9	11.1	11.08	0.52
Total	Apr/12 to Jan/14	639	748.8	35.2	37.34	1.75

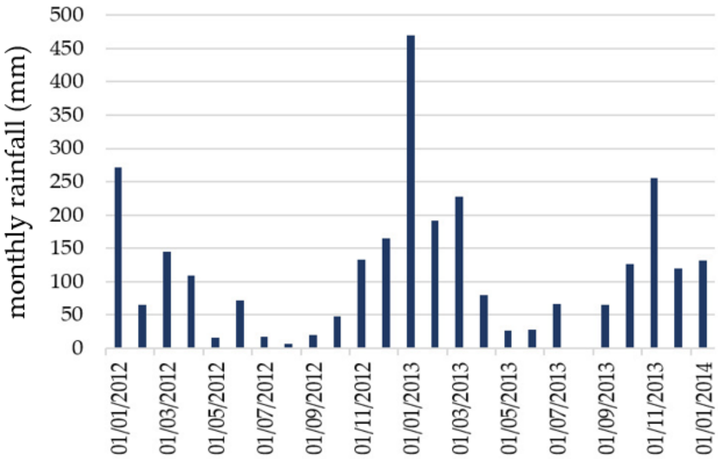

Figure 15. Monthly precipitation during the field monitoring period (2012 and 2014) at the HPP Funil Resende Aeroporto station (ANA code 2244161).

The sediments collapsed in the evolution of erosion tunnels remain stored at the bottom of the channel for a certain time, hiding the exfiltration faces in the lower portion of the edges of the incised channels and, therefore, temporarily interrupting the erosion mechanism associated with the growth of the tunnels, as previously observed by Coelho Netto and Fernandes (1990) in the Bananal River basin. This erosion mechanism is reactivated in the same location after removal of the collapsed material by surface runoff, particularly during subsequent rains that produce the so-called "*waterfall effect*" (according to ROSE et al., 2014; and SIDLE et al., 2019), as can be seen in Figure 16.

Figure 16. Detail of surface runoff during a rainy event: A- Slope surface runoff converging to the erosion channel of gully 1; B- "Waterfall Effect" at the head of the digit channel and removal of collapsed sediments; C- Surface runoff concentrated in the erosive channel and storage of sediments related to the gullying process.

Gully 02 has been developing in a headwater valley relatively smaller than the valley of Gully 01, prevailing an erosive work of lateral and upstream spreading, along the channel and at the head of the gully (Figure 17A). In addition to presenting a wider exposed soil surface and favoring the production of Hortonian-type surface runoff (Horton, 1945), the occurrence of numerous erosive tunnels also proliferates, as can be seen in Figure 17B and greater detail, in Figure 17C. These erosive tunnels and respective collapses, which account for the retreat of the low-medium slope, also favor the advance of erosion towards the divider with the Cax 1 headwater valley. The progressive reduction of the upstream contribution area is notorious, and the fact that it does not inhibit the erosive work, also suggests an additional contribution of water flows from the neighboring headwater valley, feeding the production of a temporary and suspended aquifer from the valley neighbor where the planting of eucalyptus intensified infiltration on the slope (Cax 1).

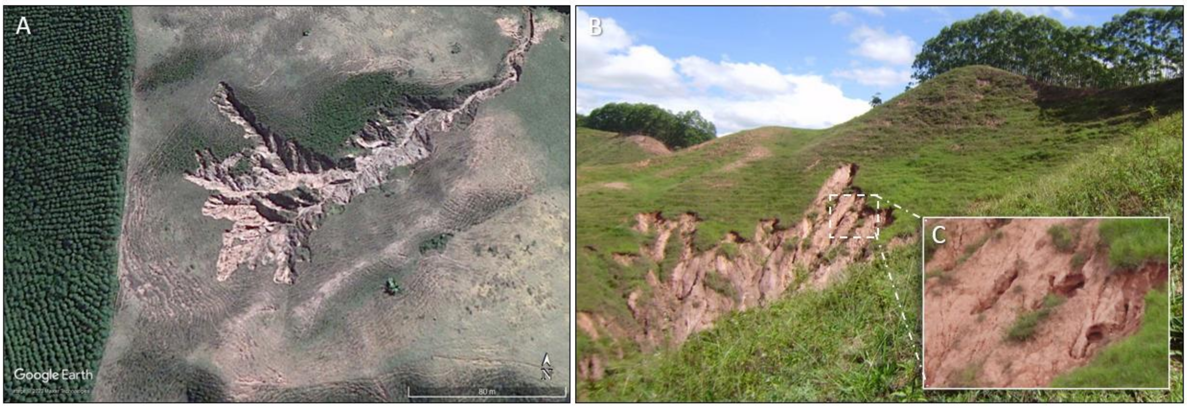

Figure 17. Erosive activity in Gully 02 of Itamarati Farm: (A) Satellite image of the incised channel of Gully 2 in 2010 and erosion spreading on the low-medium slope with multiple digits dissecting the valley in the form of an amphitheater; (B) Photograph of the upper portion of the gully in 2010 and (C) Photograph with detail of the erosive tunnels. Credit for the satellite images in figure (A): *Google Earth Pro / Maxar Technologies* and photographs (B and C): Anderson Sato.

4.2.3 Evolution of the erosion process and stabilization of gullies

The analysis of the evolutionary process of the gullies is based on the comparison of satellite images, accompanied by field observations. Figure 18 shows the evolution of Gully 01 in the right column and Gully 02 in the left column. As previously mentioned, in 2003, gully 01 was stabilized and with arboreous vegetation in its interior, while gully 02 still had a small area of exposed soil on the lower slope and steeper lateral edges, suggesting some erosive activity. However, in the period immediately after the eucalyptus plantations on the Caximonan farm, in mid-2004, both showed a more intense regressive growth in the first years and a reduction in the eroded area in the period of field monitoring between 2012 and 2014, mainly in gully 02, which remained with little apparent change in the following years. In this same figure, one can see that, although gully 01 expanded regressively in the following period, in 2016 it was possible to observe a resumption of the revegetation process in the longest channel-digit, oriented northwest towards headwater valley Cax 1; the same is observed in the small digit channels of gully 02. In 2023, the expansion of revegetation inside the two gullies can be observed, strengthening the idea that both are evolving towards a condition of stability.

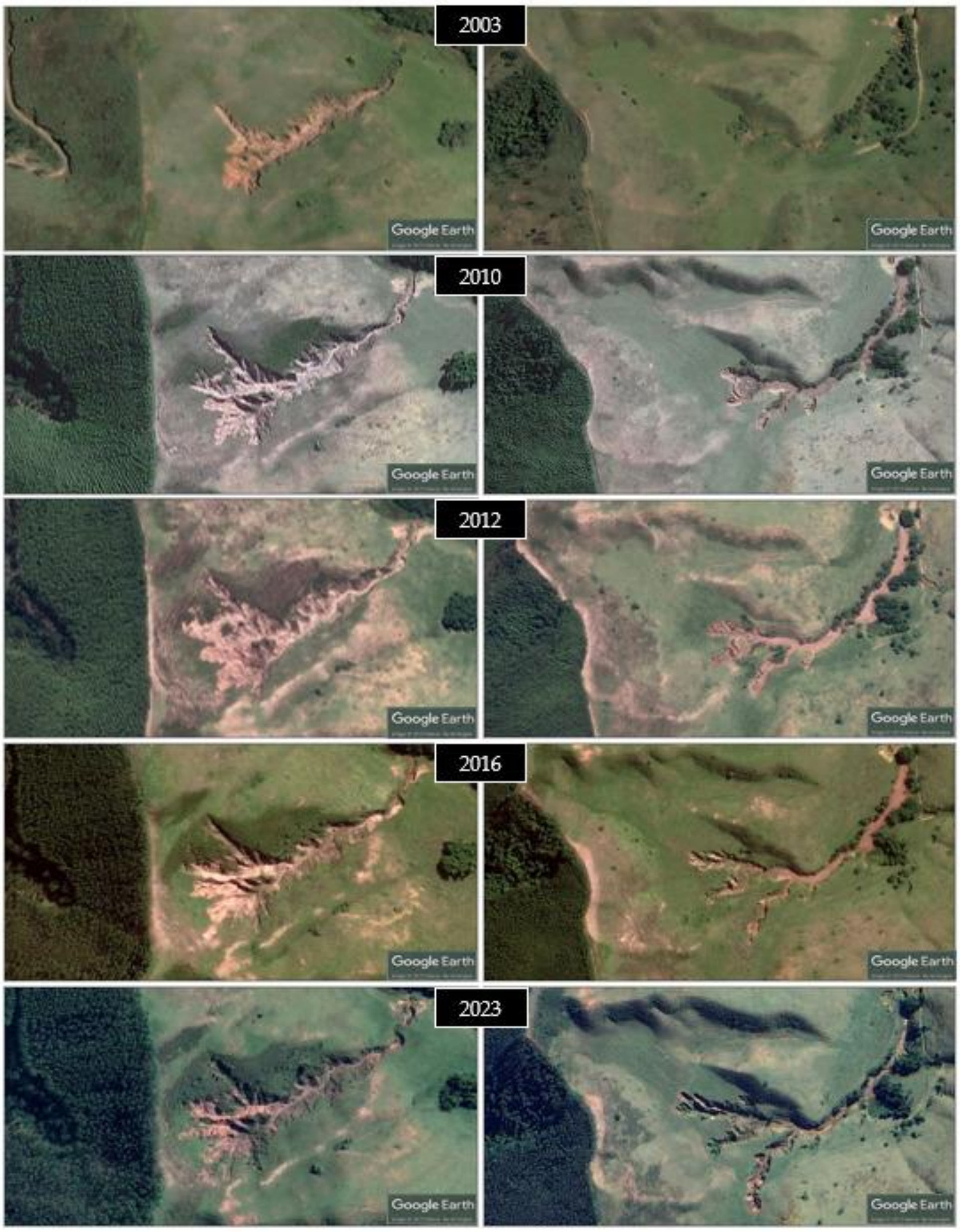

Figure 18. Variations in the morphological configuration of gullies 01 and 02 between the years 2003 and 2023 illustrate the erosive activity cycle and the ongoing trend towards stabilization and the consequent return of vegetation.

The data contained in Table 10 confirm this trend of an evolutionary process towards a new condition of stability, as indicated by the progressive reduction of the eroded area in the two gullies. Between the beginning of planting and the year 2010, the rate of erosion related to the growth of gully 01 was around 1,948.57 m²/year; between 2010 and 2012 this rate dropped to 1,253.06 m²/year; later it reduced to 356.35 m²/year and, in the last period it was only 126.14 m²/year. In Gully 02, erosion rates reached lower values, varying from around 769.55 m²/year between the beginning of planting and 2010; this rate reduced to 344.93 between 2010 and 2012, followed by a lower rate between 2012 and 2016 (154.88 m²/year), remaining practically stable in the last period, between 2016 and 2023, with a rate around of just 13.11 m²/year. Confirming this trend, it was found that in 2023 the vegetation cover inside the gullies covered an area of 2,056.89 m² in Gully 01 and 795.42 m² in Gully 02.

Table 10. Total eroded area (m²) at different time intervals and respective erosion rates (m2/year) in gullies 01 and 02 in the period between 2004-2010, 2010-2012, 2012-2016, and 2016-2023.

		2003 / 2004	2010	2012	2016	2023
Total area (m²)	Gully 01	1,612.69	13,304.13	15,810.26	17,235.67	18,118.68
	Gully 02	5,243.47	9,860.77	10,550.64	11,170.17	11,261.94
			2004-2010	**2010-2012**	**2012-2016**	**2016-2023**
Erosion rate (m²/year)	Gully 01		1,948.57	1,253.06	356.35	126.14
	Gully 02		769.55	344.93	154.88	13.11

*The erosion rate was calculated from 2004 onwards, due to the year in which eucalyptus plantations were introduced in the studied area.

4. Discussion

The slopes with eucalyptus plantations were more favorable to water infiltration into the soil than the grassy areas with pasture. This results, in part, from the interference of the thick layer of eucalyptus litter (MELOS; SATO; COELHO NETTO, 2010) which, in addition to absorbing part of the rain, promotes its gradual transfer to the soil at a rate lower than its infiltration capacity, as observed by Coelho Netto (1987) in humid tropical forest. On the other hand, the concentration of rainwater near the eucalyptus trunks (SATO; AVELAR; COELHO NETTO, 2011), combined with the preferential percolation of rainwater near the pivoting tree roots, results in more effective wetting in-depth, up to the base of the roots, even before the advance of the moisture front in the soil matrix. This behavior was also observed in heterogeneous (Tropical Humid and Secondary) forests located in other mountainous environments of Rio de Janeiro (SILVEIRA et al., 2005). In contrast, *Brachiaria* pastures have a lower infiltration capacity, probably due to soil compaction due to cattle trampling (SILVA et al., 2019), and a less dense and shallower root system, favoring the production of surface runoff.

The concentration of rainwater next to the eucalyptus trunks, in the crossing process, results in terminal precipitation in the soil with values higher than those measured in an open area, reaching terminal precipitation that, on average, is 160% greater than precipitation above the tree canopy, occasionally reaching maximum values of up to 567% on rainier days (SATO; AVELAR; COELHO NETTO, 2011). The pivoting root system, in turn, provides rapid water percolation and sudden reductions in suction at 150 cm, that is, at the terminal depth of the tree root, below -50 kPa. On grassy slopes, the fasciculated and concentrated root system up to 40 cm deep provides, on the one hand, an increase in hydraulic conductivity, but also creates a discontinuity below the root zone, favoring the saturation of this upper layer and increasing surface runoff by saturation (CAMBRA; COELHO NETTO, 2000). Studies such as those by Freire Allemão (1997), Jansen (2001), and Silveira (2004) on forest fragments of the Atlantic Forest reaffirm the role of fine and thick roots as preferential pathways for rainwater percolation in the soil profile, possibly reaching saturation at the base of the root.

The suction behavior observed at the beginning of the rainy season at a depth of 150 cm on the slope with eucalyptus, decreasing close to zero in the first rain after a long period of drought, between October and November 2015, reinforces the idea of preferential percolation of water along to pivoting roots. However, the greater delay in suction variation at other depths, even with the entry of successive rains in the same period, suggests a buffering effect promoted by the high storage capacity of rainwater in the thick layer of eucalyptus litter. This effect could be broken after a certain amount of rainfall, which may vary depending on the previous humidity conditions.

The amplitude of variation in suction behavior in eucalyptus plantations, at all analyzed depths, may be related to greater losses due to evapotranspiration, possibly associated with a greater index of leaf area and biomass. Zhou et al. (2002) in southern China, observed that soil moisture is lower in areas planted with *Eucalyptus* species than in areas with exposed soil, due to the absorption of water by the roots. On the other hand, soils with grass cover and smaller amplitudes of variation in the mean suction behavior reveal a more humid condition of the soil, especially at greater depths (Figure 7). This last result corroborates the studies by Marques et al. (2018) in the mountainous region of Rio de Janeiro, where it was found on slopes with grasses that soil water saturation is maintained at depths below 100 cm, even during long periods of drought, due to restriction of evapotranspiration in the absence of roots in depth.

On the slopes covered by grasses, the suction values at the lowest depths (20 and 50 cm) fluctuated according to the incidence of rain, however, they lost moisture more easily due to the evapotranspiration process. It is relevant to observe that station G1, located on the slope adjacent to the eucalyptus plantation, presented the lowest suction values at greater depths (150, 200, and 300 cm), than on the slopes with grass (G2) without the influence of these plantations on its neighborhood, suggesting the occurrence of migration of subsurface water flows from the slope with eucalyptus plantation. This idea is strengthened by the fact that the headwater valley planted with eucalyptus is in a higher topographical position than the valley bottom of headwater G1, favoring the migration of underground water flows from the valley with eucalyptus and, thus, increasing the discharge of water on the exfiltration faces and the erosive work on the medium-low slope of headwater G1.

The NA altimetric variations between the valleys of adjacent headwaters influence the hydraulic gradient between them, favoring the direction of underground water flows towards the most dissected valley floor, that is, lowered by the increasing incision of the gully-type erosive channel (LEAL et al., 2015). In the present study, it was observed that the highest NA in headwater valley Cax.2, concerning the two neighboring valleys where gullies 01 and 02 develop, contributed to the erosive reactivation in these two gullies after the increase in infiltration with the eucalyptus plantation on the slopes of Cax.2. It is worth mentioning that the NA in all wells monitored at the Cax2 station (average elevation of the NA P1= 522 m; P2 = 523 m; P3 = 528 m) are higher concerning the bottoms of valleys with active incision in the gullies.

The synchronism in the upward movement of the NA in all wells, regardless of their depth and altimetry, suggests that the valley bottoms of drainage headwaters are influenced by the dynamics of the regional aquifer, in addition to the hydrological behavior on the slopes and local rainfall. This regulation of the regional aquifer was also observed in the Bananal river basin, where subsurface water level variations, as well as piezometric loads, respond to rainfall at the regional level and with similar delays, varying between 2 and 4 months (FONSECA et al., 2006; LEAL et al., 2015). Coelho Netto (1999) points out that the high topographic gradient observed in the Bananal River basins (0.040 dimensionless) and in the Sesmaria River basin (0.055 dimensionless) favors the generation of artesian flows, through the fracturing of rocks, with higher piezometric loads along the axes of the headwater valleys, particularly in the hill domain. These artesian flows are primarily responsible for the formation and expansion of incised gully-type channels, which grow regressively along the valley axes, as in the case of gullies 01 and 02. This fact, however, does not exclude the effects of local recharge favored by eucalyptus plantations, both locally and in lateral migration to neighboring valleys, increasing the exfiltration rate on the low-medium slope, as seen in the case of gully 02; that is, enhancing the temporary and shallower subsurface water flows in the rainy season, as observed in the numerous points or faces of exfiltration, intensifying the erosive work and the retreat of the slope.

Leal, Coelho Netto, and Avelar (2015) in a study in pasture areas of the Bananal River basin physically modeled the dynamic behavior of the underground water flow network, between valleys of adjacent headwaters with spatial and temporal variations of the hydraulic gradient in response to the expansion of the channel network, calling this migration of flows between adjacent valleys "*groundwater piracy*" as an inducer of the acceleration of the retreat rates of the gully channels. Leal (2009) noted that groundwater piracy can occur between headwater valleys with low elevation differences, depending only on the amount of water available in the system. In fact, in digit D4, which grows obliquely towards the topographic divide, forming the limit with the Caximonan farm, more effective erosive work on its left side edge than on the right edge was observed, evidenced by the occurrence of numerous erosive tunnels that attest to the greater discharge of water on the exfiltration face and the greater rate of retreat of the gully head (Figure 13B).

The evolution rates of digits in Gully 01 were significantly higher than in Gully 02, both linearly and in area (Table 9). For comparative purposes, a survey carried out by Bull and Kirkby (1997) on the average expansion rates upstream of the gully heads, in different study areas, indicated that these can expand up to 6 m per year. These rates are lower than the rates observed in this study, expressing that the magnitude of the erosive work, reactivated with the change in land use, can reach values above the expected behavior, revealing that the mode of intervention in land use has exceeded the threshold of its support capability.

In the evolution of Gully 02, the participation of the permanent regional aquifer at the bottom of the erosive channel expresses a connection with rainfall at the regional level, while in the low-medium slope the participation of the suspended, temporary aquifer operates in direct response to local rainfall. The permanent underground water flows operate the erosive work mainly at the bottom of the incised channels and, although the rhythm of their fluctuations is synchronized between the headwater valleys, the volumes and water levels of these valleys are not spatially uniform. Locally, eucalyptus plantations favor the infiltration and local recharge of these aquifers, which can activate the erosive work both by exfiltration of the regional aquifer at the bottom of the incised channel, as well as at the edges of this channel and on the low-medium slope of the head of the valley.

The gullies studied in this work show that the variable erosion rates, observed over two decades, showed a more intense response soon after planting eucalyptus in the adjacent headwater valleys of the Caximonan farm, which progressively decreased over the sample period between 2004 and 2023. If, on the one hand, the erosive reactivation responded immediately to the change in land use due to alterations in the hydrological regime between the slopes of adjacent headwater valleys, on the other hand, the progressive reduction in erosion rates reveals the search for a new internal adjustment of the hydro-geomorphological system, that is, a new condition of stability. The erosive reactivation of gullies 01 and 02, resulting from the internal imbalance caused by the change in the drainage system, is, therefore, a temporary process that, in the case studied, was and still is around two decades old.

It is worth mentioning, however, that other groundwater exfiltration faces are also observed in road cuts where, in the absence of efficient drainage works, erosion due to excess water pore pressure on the exfiltration faces is observed. Field observations carried out on the Queluz-Areias highway (SP-058) in the state of São Paulo attest to the occurrence of this erosion mechanism, opening erosive tunnels and punctual collapses, but also inducing landslides, particularly along the axis of a concave up topographic hollow or headwater valley as illustrated in Figure 19. Figure 19A shows the two-year-old eucalyptus plantation on the upper portion of the slope, below which a cut was made for the construction of the highway and finished in the form of terraces to control surface erosion, ignoring efficient drainage of the temporary underground runoff, whose exfiltration led to numerous erosive tunnels, followed by earth collapses, and also, by landslides in the axis of the drainage headwater valley. Another case can be seen in the same Figure 15B, on another farm located in the Sesmaria river basin, whose regressive advance of the digit channels of a gully at the bottom of the valley reached the low-medium slope, reaching the upper portion with eucalyptus plantations.

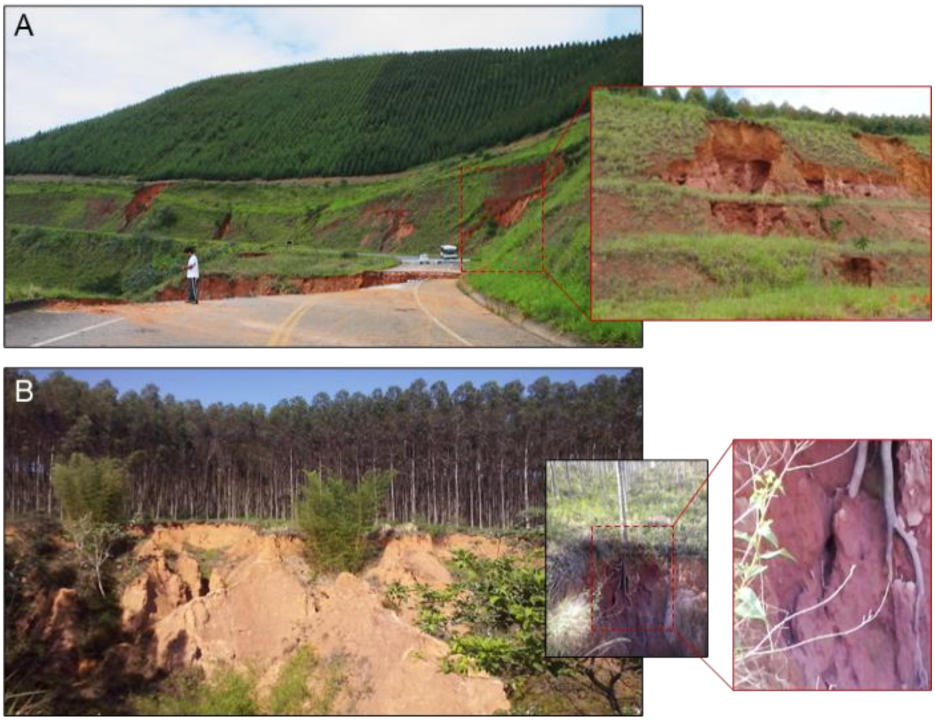

Figure 19. Erosions due to (temporary) groundwater runoffs downstream of eucalyptus plantations. (A) Queluz-Areias Highway (SP-058) with occurrence of landslide; (B) Evolution of erosive digits following planting alignment orientation exposing the eucalyptus root system in another farm upstream of the area monitored by this study, in the Sesmaria river basin.

5. Conclusions

The studies carried out in the hills of the Sesmarias basin allow us to conclude that, unlike heterogeneous forests, within eucalyptus plantations, the concentration of rain close to the tree trunk, combined with the preferential percolation of water along the pivoting tree roots, provides rapid injection rainwater and recharge of temporary and permanent aquifers. On the other hand, the plant litter layer produced by eucalyptus, with a water retention capacity similar to that observed in humid tropical forests on the slopes, but much thicker due to the artificial reduction of the decomposing fauna (use of chemical pesticides during planting), contributes to the delay of the advance of the moisture front in the soil matrix. Under such conditions, the low production of surface runoff on the slopes restricts erosive activity by raindrop splashing and surface washing on the planted slopes, which is restricted to the dirt roads used for planting and wood harvesting. It is configured, therefore, as a favorable environment for erosion mechanisms by the action of temporary and/or permanent groundwater flow as is observed in the erosive reactivation of gullies with regressive growth and, in large part, connected in the expansion of the regional channel network.

In the hydrological behavior of the slopes monitored in eucalyptus plantations and grasses with extensive pasture (coverage before plantings), the change in the storage of water in the soil was evident: grasses, with fasciculated rooting and concentrated in the first 40 cm of depth, restrict losses of water by evapotranspiration and favor the storage of water at greater depths, even in periods of prolonged drought, sustaining lower suction values than in eucalyptus plantations. These, in turn, are close to the behavior observed in (tropical humid secondary) heterogeneous forests with fast and larger amplitudes of variation of the suction in the soil profile as well as in the fluctuations of the groundwater level. These water levels vary between the headwater valleys and, internally, have the NA closest to the land surface at the bottom of the valleys, as expected.

Local NA variations revealed the importance of the hydraulic gradient between adjacent headwater valleys in directing the groundwater flow network, converging the flows towards the valleys where the linear incision of the gully channels resulted in the lowering of the valley bottom and, therefore, the water table, allowing the transfer of flows between adjacent valleys, called "groundwater piracy", as defined in the Bananal River basin by Leal, Coelho Netto and Avelar (2015). It means, therefore, that the change in land use with eucalyptus plantations, which potentiated the injection of water into the soil and activated or reactivated the growth of gullies, also altered the network of underground flows, intensifying erosion on the exfiltration faces and, especially, at the bottom of valleys. In this sense, the already stabilized gullies, or in the process of stabilization at the bottom of the valleys, also contributed to their reactivation, feeding back the regulating system of the erosive work that is responsible for the formation and reactivation of the incised channels. This illustrates that the surface forms are, at the same time, the result of and conditions of its evolution, without excluding the appearance of new incised channels of the gully type, as observed after the planting of eucalyptus.

Responding to the increase in infiltration after these plantings, temporary and suspended aquifers can also activate new erosion foci due to excess pore pressure on the exfiltration faces, forming erosion tunnels that collapse after a certain amount of development. Even on the low-medium, steep slope, new exfiltration faces may appear, occasionally triggering erosion, but usually on exposed soil, naturally or by human intervention, as observed in the study area and highway cuts downstream of the eucalyptus plantations.

Finally, it is worth noting that changes in land use, as seen in this study, induced significant changes in hydro-erosive processes, intensifying erosion and silting rates in the channel network, resulting in harmful effects in short and long distances. However, this reactivation and intensification of erosive work has a period of readjustment of the drainage system in the search for a new period of stability, as seen through the decreasing erosion rates monitored in this study. Indications of yet another period of stability reveal the discontinuous or episodic nature of the evolutionary process of the channel network, which may be a consequence of a new adjustment of slopes between adjacent headwater valleys and/or adjustment to the new environment.

Funding: This work was carried out under INCT-MCTI/CNPq/CAPES/FAPs no. 16/2014: INCT-REAGEO/ Geotechnical Institute for Rehabilitation of the Slope-Hillside System and Natural Disasters; with the support of the National Council for Scientific and Technological Development (CNPq) through public notice CNPq Universal 14/2011 - Range B (Case No. 480.293/2011-2); support from the Research Support Foundation of the State of Rio de Janeiro (FAPERJ) through the public notices FAPERJ 11/2012 Environment (Case No. E-26/111.364/2012) and the Program Scientist of Our State FAPERJ (Case No. E - 26/102,791/2008), as well as doctoral, master's and scientific initiation scholarships granted by CNPq and FAPERJ.

Acknowledgments: The authors would like to thank the reviewers of the article for their contributions.

Authors contributions: FACADIO, A.C.C. – Conception, Methodology, Validation, Investigation, Writing – initial version, Writing – revision and editing; SATO, A.M. – Conception, Methodology, Validation, Investigation, Writing – review and editing; COELHO NETTO, A.L. – Conception, Methodology, Validation, Investigation, Resources, Writing – review and editing, Supervision, Project administration and Acquisition of funding.

Conflict of Interest: The authors declare that there is no conflict of interest. Funders had no interference in the development of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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