Groundwater-induced Seasonal Slumps in Gullies of the Bação Complex, Southeastern Brazil

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Abstract

Areas with a high density of large-scale gullies are frequent in regions of the crystalline basement of southeastern Brazil, such as the Bação Complex. These gullies pose a high risk for people and properties, and cause loss of agricultural land, silting up and flow reduction of waterways, among other impacts. Gullies originating as erosion by channelized surface runoff can be controlled relatively easily by ordinary containment practices. However, when erosive channels reach the groundwater, erosive processes conditioned by subsurface flows start acting, causing mass movements and their control becomes more difficult. Continuous field monitoring shows that these mass movements occur not only in the rainy season, as expected, but also in the dry season. To understand the dynamics of mass movement in the evolution of these features, a representative unstable gully in the Bação Complex was selected. As it is common in this region, this gully presents very steep and unstable slopes, especially due to slumps. Numerical simulations of saturated and unsaturated flow have shown that, in this region of high seasonality, the aquifer is recharged in two stages. Safety factor analysis by limit-equilibrium method indicates that slumps occur during the rainy season, when the aquifer at the toe of the slope is recharged, and in the dry season, when the upper slope is recharged after a few months' lags due to thicker unsaturated zone having slower water flow. Finally, a low-cost stabilization method was proposed involving the construction of alternative drains and retention walls.

1. Introduction

Erosion in channels may have serious impacts, particularly in tropical regions, where they can attain large dimensions, due to their tendency to form deeper weathering profiles. In Brazil, these are referred to as *ravines* i.e. those formed only by surface erosion mechanisms, and gullies (or "voçorocas") that also involve subsurface erosion (Guerra 1995). This classification has a practical basis, because ravines can be easily controlled by surface water containment, while gullies require controlling mass movements and subsurface erosion caused by the exfiltration of groundwater, which is much more complex.

Gullies are quite common in regions that have deep and erodible soil profiles, such as those on crystalline basement or psammitic sedimentary rocks (Okagbue and Ezechi 1988; Bacellar 2000). Gullies usually develop rapidly, constituting a geodynamic process that causes immense economic, social, and environmental damage. This includes loss of agricultural soil, destruction of buildings and habitat of fauna and flora, change in hydrological regime, siltation of channels and hydroelectric reservoirs, in addition to lowering of the phreatic surface, with baseflow reduction and drying of springs (Bacellar et al. 2005; Costa and Bacellar 2007; Lima et al. 2018).

The Bação Complex, an area with crystalline basement rocks, is one of the most intensely affected areas by gullying in the world, with 225 large-sized gullies mapped in an area of 375 km^2 (Bacellar et al, 2005), causing the elimination of approximately 1.35×10^7 m^2 of farmland (Lima et al, 2018). Erosion in this region is facilitated by the thick soil profile, with a very erodible saprolite of low shear strength. The erosion in the Bação Complex is initiated by surface processes and when the water table is reached at the base of the saprolite, the erosion processes induced by groundwater water are initiated. As the soil profile has a great water storage capacity, its removal by erosion reduces the aquifer recharge by about 7.5×10^7 m^3, decreasing water availability in the dry season in this region (Lima et al. 2018).

To prevent the progression of gullies, the common practice in the region is to divert the surface waters with terracing on contour lines. However, this practice is ineffective, since gullies grow mainly due to mechanisms controlled by the exfiltration of the water table at the base of slopes, with emphasis on mass movements, especially *slumps* (Bacellar, 2000; Lima et al. 2018). Futai (2002) inferred that these slumps develop because of the apparent loss of cohesion of the exposed soils on gully slopes due to saturation during the rainy season. Therefore, they could be stabilized through measures of surface protection on unstable gully slopes, using vegetation or geotextile blankets.

However, it has been found that such slumps are also frequent in the dry period, due to the late recharge of the aquifer, as demonstrated by Drumond (2006). The groundwater recharge time lag of several months, measured in piezometers by this author, is due to the high thickness of unsaturated soil on the subvertical slopes of the gullies. Hence, the above gully-stabilization measures that target only surface saturation of soils are ineffective.

Therefore, the main objective of this study was to investigate the influence of the water flow regime in the saturated and unsaturated zones of the soil profile on the degree of stability of the slopes of these gullies. It was selected an unstable slope on a representative gully in the Bação area and collected detailed data to carry out analysis, which included numerical simulation of flow by finite element method, coupled with analysis of the degree of stability to slumping by limit-equilibrium method. The import of flow simulation results, as proposed here, is preferable to the simple addition of the water table in slope stability analyses, as usually done. This is because the numerical simulation of unsaturated and saturated flow makes it possible to better analyze the influence of hydraulic gradients, often with vertical components, on slope stability.

Using these results, an innovative and low-cost measures for gully stabilization was proposed. It is important to note that this study can be useful in the context of this densely populated region of high economic and historical relevance for Brazil, which is intensely affected by gullies that pose a high risk to the inhabitants.

2. Study Area

The Bação Complex is the crystalline basement of the Ferriferous Quadrangle, which is one of the most important minerals provinces worldwide, with large reserves, particularly of iron and gold, in the supracrustal rocks of the Rio das Velhas and Minas supergroups (Door 1969; Alkmim and Marshak 1998).

This complex of Archean age covers approximately 385 km^2, and outcrops in a structural window between the supracrustals (Figure 1). It is composed predominantly of banded, variably migmatized gneisses from tonalitic-throndjemitic-granodioritic composition, intruded by granitoids, and subordinately, by mafic and ultramafic rocks (Gomes 1986; Noce et al. 1998; Lana et al. 2013).

A polyconvex (*mar de morros*) or slightly aligned hill relief predominates the area, with a dendritic or angular dendritic drainage (Bacellar 2000). The weathering profile can attain a thickness of up to 50 m in gently sloping areas, where Ferralsols develop. Here, the saprolite thickness (horizon C) is tens of meters, the pedological horizon Bw (solum) is 2–10 meters and that of horizon A is a few decimeters (Bacellar 2000). The saprolite, having a silty-sandy texture, is characterized by low hydraulic conductivities (3.7×10^{-6} cm/s < K < 6.6×10^{-5} cm/s) and high erodibility (Bacellar 2000; Morais 2003; Bacellar et al. 2005). Although the solum has a predominantly sandy-clay texture, its hydraulic conductivity is high (1.0×10^{-4} cm/s < K < 9.2×10^{-4} cm/s) and has low erodibility due to aggregation of fine particles by iron oxides and hydroxides, typical of highly evolved tropical soils (Bacellar 2000; Bacellar et al. 2005). Cambisols develop in the steepest areas, and Fuvisols and Histosols in valley floors (Bacellar 2000).

The climate of the Bação Complex is classified as CWa (Koppen classification), with a rainy season between October and March, and a dry season between April and September. The average annual precipitation is 1348 mm, within the range 1024–1744 mm (Bacellar 2000), which exceeds evapotranspiration, resulting in an effluent drainage system. The vegetation is classified as semi-deciduous seasonal forest and is considered as a transition zone between the "*Cerrado*" (Brazilian savannah) and the Atlantic forest domains (Santos et al. 2002).

The flatter areas of the Bação Complex have a high concentration of gullies of large dimensions (Figure 1b) that are up to 400–500 m long, 150 m wide, and 50 m deep (Bacellar et al. 2005). This study was conducted on one of the largest gullies in the region, located in an area known as the Holland monitoring station on the southern part of the complex (Figure 1). Like most other gullies in the complex, this gully lies in an urban expansion in the Santo Antônio do Leite county posing a potential risk to the occupation.

These gullies begin as small rectilinear rills of erosion due to surface runoff. Although the solum is resistant to erosion, the concentration of runoff water, exacerbated by various human activities since the end of the 17th century (Bacellar 2000), can erode it to form ravines. When the phreatic surface normally situated at the saprolite base is reached, the gully is extended by the centripetal force of percolating groundwater and gradually acquires a more rounded form. The erosion-resistant solum forms a protective cover for the saprolite, resulting in very steep gully slopes that are often subvertical in the middle and upper thirds (Bacellar 2000).

The soil has excess water during wet months, however, due to the high thickness of the unsaturated zone consisting largely of saprolite, the recharge of free aquifers involves a high lag time. Drumond and Bacellar (2006) used Casagrande piezometers installed in a gully nearby (Mangue Seco gully), where the water table was approximately 20 m deep (Figure 2a) and identified a lag time of ~5 months between the onset of rains (October) and the beginning of the phreatic surface recharge (March). This high lag time was also apparent in the hydrogram of the drainage channel of this gully outlet (Figure 2b) and was also recognizable in annual hydrographs of drainage channels in some catchments of this region (Figure 2c). In fact, in catchments with gullies, the water table tended to be lowered by these erosive features that functioned as drains, thereby delaying the recharge and consequent base flow in comparison to gully-free catchments (Figure 2c).

Hence, gullies initially evolve by surface erosion processes, but when the phreatic surface is reached, various groundwater-induced processes become more important, including several types of mass movements, particularly slumps, which involve the entire soil profile and have sound rock as a basis (Drumond and Bacellar 2006). Hence, controlling surface flow does not prevent the progression of gullies in the region (Bacellar 2000). Drumond and Bacellar (2006) also point out that while these processes prevail during the rainy season, small mass movements develop in the gully slopes because of the delayed ascent of the phreatic surface. The authors identified creep and flow slides of saprolite by liquefaction as main movements (Figure 6). According to Drumond and Bacellar (2006), such instabilities would explain the large volume of soil transported in suspension through internal drainage channels during the first summer rains, indicating soil mobilization on gully slopes in the dry season. This means that during the dry season the slopes are progressively undercut, and the soil dislodged inside the gully is eliminated with the first rains.

Futai (2002) investigated the mechanisms that likely favor slumping of the gully slopes because this process is fundamental to understanding the evolution of these features. This author mechanically characterized only the soils of horizons Bw and C, as horizon A is shallow and is usually eliminated by sheet erosion (Bacellar 2000) near gullies.

Performing triaxial tests with servo-controlled suction on soils in the gully areas, Futai (2002) found shear strength increasing with depth. Horizon C presented cohesion values of 2–38 kPa, with an angle of friction of 26.4°–31.6°. The pedological horizon Bw showed cohesion of 8 kPa and friction angle of 27.7º (Futai 2002). In this case, the steep slopes of the region's gullies likely become unstable by an apparent loss of cohesion during rainy periods. However, field observations and laboratory test results showed that saturation only occurs at the toe of the slopes, with the exfiltration of groundwater.

3. Methods

For this study, it was selected the area known as the Holland monitoring station, which has a large repository of geological, geotechnical, and hydrogeological data (Parzanese 1991; Bacellar 2000; Silva 2000; Futai 2002). There are two large gullies at this site, with slopes affected by mass movements, especially slumps (Fig. 3). An aerophotogrammetric map of the area was carried out with a drone to develop a 1:3000 scale digital elevation model. For this study, the focus was on the eastern gully *(*Gully 1, Fig. 3a).

Despite the large volume of existing soil geotechnical data, a basic characterization tests were performed, including soil texture and plasticity, following international standards. For this, deformed and intact samples were collected from trenches and gully slopes from horizons Bw and C (saprolite), since horizon A was largely eroded. Hydraulic conductivity was measured in undeformed samples using the variable-head permeability test. The variation in soil suction with soil moisture in the drying path was assessed with the filter paper technique of D5298-16 ASTM (2016) standard. Laboratory data for the water retention curve were adjusted following Gitirana and Fredlund (2004), a method suitable for tropical soils, which often exhibit porous space with a bimodal distribution. The hydraulic conductivity function was then adjusted with the method proposed by Fredlund et al. (1994), using Geostudio (2020a) software SEEP/W module.

The shear strength parameters of the soils were obtained from Futai (2002). Since the saprolite shear resistance increases with depth, the maximum parameters of cohesion (38.0 kPa) and angle of friction

(31.6°) were adopted for this horizon. For the analysis of the shear strength the ϕ^b linearity in the extended Mohr-Coulomb failure envelope of unsaturated soils, as defined by Fredlund et al. (1978), was assumed.

The climate data were obtained from INMET (Brazilian weather center) weather stations. Precipitation was measured with a pluviometer located proximately and potential evapotranspiration determined by the Thornthwaite (1948) method with photoperiod, average temperature, and relative air humidity data. The actual evaporation was calculated by the method of Wilson et al. (1997) available in the SEEP/W module (Geostudio, 2020a).

For stability analysis, a representative section (Fig. 3b) was selected according to historical data, in addition to *in situ* observations, according to the advance of the slump gullying process. The NW slope of Gully 1 was highly unstable, as reported previously (Bacellar 2000). This was corroborated by the absence of vegetation on the slope and the presence of small, recent slipping scars (Fig. 3b).

The geological model of the section was based on previous data from auger and SPT borings and geophysical surveys of electrical resistivity and GPR (Bacellar 2000). However, some vertical electrical soundings (VES) were conducted to better identify the position of the water table and the top of the sound rock. The obtained VES were inverted using the IPI2Win-1D software (2000).

This representative section was used for numerical simulations of flow analysis by finite elements in the SEEP/W module of the Geostudio (2020a). The analysis was initiated with a permanent flow simulation for establishing the initial flow conditions. Subsequently, the conditions of transient flow in the hydrological year between 10/01/18 and 09/30/19 were simulated.

The permanent and transient flow numerical simulations were validated with the water table position assessed using electro-resistivity and by comparing with seasonal piezometric data compiled by Drumond (2006) and simulated by Lima (2016) in Mangue Seco gully, which presents remarkably similar characteristics to the studied gully.

The slope stability analysis was conducted on the SLOPE/W module on Geostudio (2020b), using the limit-equilibrium, with Morgenstern and Price (1965) method. The stability analyses were coupled with flow analyses to assess the seasonal variations of the safety factor.

Choosing the appropriate stabilization method is particularly important considering the variety of factors that influence the advancement of these gullies. Therefore, a potential stabilization method proposed by Prandini et al (1974) was also assessed.

4. Results And Discussion

The climate data for the hydrological year 2018–19 illustrate the local climate seasonality, with rainfall concentrated between October and March (972mm), and a dry season between April and September (199.1 mm). The annual precipitation in this hydrological year was 1171.1 mm, below the regional average (1348 mm), but within the measured range, between 1024 mm a 1744 mm (Bacellar 2000). This drought was a consequence of an abnormally dry January, a phenomenon regionally called "*veranico*" (dry spell). The potential evapotranspiration estimated using the Thornthwaite (1948) method was 1099.5 mm, with higher values in the dry season, when actual evapotranspiration is lower. The cumulative water balance, based on the actual evaporation (Wilson et al. 1997), showed the climatic seasonality, with an excess of water during rainy months and deficit in the dry months.

The two gullies in the Holland station are on the side of a hill gently sloping to the south and southeast (Fig. 3a). On the gully slopes, it is possible to see that saprolite has decametric thicknesses, while horizon Bw is 2–10 m. Horizon A is almost completely eroded.

The erosion rills on the gully slopes occur only in the saprolite, confirming its greater erodibility. As a result of the lower erodibility of the solum (Bw horizon), the slopes are subvertical in the upper third part. Gully 1 has a maximum height of ~50 m in the most critical section, an average width of 250 m, and length over 310 m. Sound rock occurs at the bottom of the gully and the phreatic surface occurs at the base of the saprolite. In the satellite image of 05/31/19, in the dry season and after 15 days with no precipitation, there is a large effluent flow at the base of the slopes of the two gullies feeding the main channel (Fig. 3b).

The intact vegetation indicates that some slopes are more stable, while bare slopes, such as those located in the northwest section of Gully 1 and the northern extremity of Gully 2, are unstable (Fig. 3b). A comparison of historical aerial photos shows that the two gullies in the area have expanded not only in the direction of the topographic slope but also in other directions due to the influence of subsurface erosion processes induced by the centripetal force of groundwater percolation. In other words, although the topographical slope is northward, both gullies are expanding even to the south, mainly by the action of slumps.

The gneiss outcrop at the bottom of the gully shows narrow banding, conferred by alternating feldspathic-quartz bands with ferromagnesian minerals ones. This gneiss is moderately fractured, but the fractures are largely filled with kaolinite, resulting in a very low hydraulic conductivity of the rock mass. The overlying saprolite presents variegated colors and inherits the banded structure of the rock, but this does not significantly influence shear strength (Futai 2002). The pedological horizon Bw (solum) is solid, reddish-brown, or yellowish, with a clayey texture, but with granular structure, as typical in well-evolved tropical pedological horizons (horizon Bw, of Ferrasols). The solum characterization test results confirm its clay texture (Table 1), qualifying as high-plasticity clays or silts according to the USCS classification (D2487-17 ASTM 2017). The saprolite has a silt-sandy texture and is classified as a low-plasticity silt. The hydraulic conductivity is greater in the solum due to the aggregation of clay particles, which confer high porosity, as is common in tropical soils (Lacerda 2010). These data are similar to those from other studies conducted in the region (Parzanese 1991; Bacellar 2000; Bacellar et al 2005; Futai 2002; Morais 2003).

Table 1

Physical and hydraulic parameters of soil horizons

Soil Horizon	LL	IP	γ_{nat} (kN/m^3)	w (%)	Gs	e	S (%)	n (%)	k (cm/s)
Solum (Bw horizon)	51	31	13.54	31.5	1.545	1.42	34.27	58.703	7.00×10^{-04}
Saprolite (C horizon)	44	NP	15.67	17.24	1.578	0.891	30.53	47.13	6.45×10^{-05}

The retention curves and hydraulic conductivity functions of both soil horizons are represented in Figure 4 and the adjustment parameters in Table 2. The obtained results were in agreement with those by Futai (2002) in the same area. The solum exhibits a bimodal behavior, typical of well-evolved pedological horizons like Bw (Carvalho and Leroueil 2000). Horizon C also presents bimodal behavior, unusual for this type of soil, but already identified in the area by Futai and Almeida (2005). If the minimum limit to drain macropores is set as 10 kPa suction (Marshall 1959), the solum, unlike saprolite, is distinguished by the large volume of macropores. This favors infiltration and decreases the surface flow, consequently reducing erosivity, in contrast to the behavior of the saprolite.

Table 2

Parameters of the Gitirana and Fredlund model (2004).

Soil Horizon	θ_s	ψ_{b1}	ψ_{res1}	S_{res1}	ψ_{b2}	S_b	ψ_{res2}	S_{res2}	a	R^2
Solum (Bw horizon)	0.5868	1.42	11.28	0.432	7601.8	0.405	17454.0	0.052	0.085	0.981
Saprolite (C horizon)	0.4712	15.00	30.00	0.67	180.0	0.62	6000.0	0.080	0.030	0.993

Systematic monitoring of several gullies in the region during the last 20 years has shown that surface erosion processes are important in the early stages of erosion in channels; however, when the water table is reached, subsurface processes become more prominent. The influence of surface flow becomes less relevant as measures to contain floods such as terraces on contour lines, also adopted upstream of the gullies of the Holland station, are often unsuccessfully deployed in the region (Fig. 3b).

The gullies in the region exhibit the following mechanisms of erosion (Bacellar 2000; Drumond and Bacellar 2006): rotational slides (slumps*)* mobilizing the whole slope; falling soil blocks from horizon Bw, which break by tension (tension joints) over the saprolite that is eroded by plunge-pool erosion; wash, rill and splash erosion of saprolite exposed on slopes; boiling and piping erosion and creep or small flow slides of saprolite in the area of exfiltration of the phreatic surface at the toe of the slopes (Fig. 5).

As already verified by Drumond and Bacellar (2006), the creep and flow slide processes in these gullies intensify in the dry season, when the phreatic surface rises due to delayed recharge. It is possible to verify that in May 2019, already in the dry period and after 15 days of drought, the volume of exfiltrating water from the aquifer at the base of the slope of these gullies was extremely high (Fig. 3b). Consequently, the gully slopes are vulnerable to the action of these two processes, facilitating subsequent development of slips. Therefore, the undercutting of the slope base during the dry period is fundamental to the continuous advancement of gullies (Fig. 5b).

To better understand the role of water dynamics in the seasonal behavior of slope stability, it was performed a slope stability analysis coupled with a numerical model of groundwater flow in a geologically representative section of an unstable slope in the northwest sector of gully 1 (Fig. 3b). Data from previous surveys and geophysical mapping, such as electrical resistivity and georadar (ground penetrating radar) (Bacellar 2000) were used to build the conceptual model. To resolve ambiguities, particularly regarding the actual position of the groundwater and the top of the sound rock, additional geoelectric data were acquired (vertical electrical soundings - VES).

The joint processing of these data allowed to build a conceptual model of the soil horizon distribution, the top of the sound rock, and the position of the phreatic surface, from which the analysis section was built (Fig. 6a). The natural slope has an average magnitude of 12.2 %. At the gully face, the eroded slope has sub-vertical declivities towards the top (maintained by the more resistant solum) that softens towards the inner gully channel, with a permanent drainage. In the direction of the topographic divider, it is possible to notice that the overall thickness of the weathering cover decreases, from 6 m to 2 m for solum and from 38 to 22 m for saprolite. The water table is on average 18 m deep in the divider and 26 m under the erosion ridge, with an average hydraulic gradient 0.1–0.4% under the natural slope, increasing in the eroded portion of the slope caused by the lowering of the aquifer by the gully.

The hydrodynamic parameters for simulating the saturated and unsaturated flows were obtained in hydraulic conductivity tests (Table 2) and characteristic curves (Fig. 4). The boundary conditions specified for the finite element simulation (Anderson and Woessner, 2002) were: specified flux (Type 2), such as impermeable border at the base (contact with the gneissic rock mass) and on the right (hydraulic boundary on the drainage divider) and at the top (specified flux by weather conditions); known head (Type 1) at the left border, where occurs the drainage channel inside the gully.

Results of the subsurface flow analysis under transient regime along the hydrologic year revealed two distinct patterns: one on the eroded slope and the other on the natural slope (Fig. 6a). The phreatic surface in the corresponding hydrological year varied more on the eroded slope (2.97 m) than on the natural slope (maximum variation 1.24 m) and the hydraulic gradients for the eroded slope have lower values during the wet season (0.66) than at the peak of the dry season (0.77). The decrease in the hydraulic gradient and the higher variation in the hydraulic head on the eroded slope is caused by the faster recharge due to the lower thickness of the unsaturated zone in this section (Fig. 6a). It is also worth mentioning the high vertical upward flow component throughout the hydrological year, which is manifested by the presence of soil boiling points in some stretches, especially in the dry season.

A water balance enabled an estimate of the water exfiltration flows on the gully face, showed the highest value in January (3.57×10^{-6} m^3/s), and a second high in May (3.30×10^{-6} m^3/s), which falls again until the end of the dry season. These results are similar to the ones presented by Drumond and Bacellar (2006) for the flow in the drainage channels of a gully in the region, with large flows in the rainy season and an increase in the dry period due to the increase in the base flow (Fig. 2b).

Slope safety factor analysis was conducted in the same hydrological year, by importing the flow simulations (head distribution) and not adding the phreatic surface, as is usual in this kind of approach (Ventura and Bacellar 2011). It then became possible to analyze the influence of the hydraulic head magnitude and direction in the saturated and unsaturated zone on slope stability. When the phreatic surface is just added in a limit equilibrium analysis, it is wrongly assumed that the water flows are horizontal and the head equipotentials vertical. It was noticed that the critical slipping surface throughout the hydrological year showed little variation in the safety factor (Fig. 6b, c), always remaining in the potential range of rupture, as is expected for such unstable slopes. A bimodal behavior of the safety factor is observed, with two minimum values, one at the height of the rainy season in January (01/01/19), influenced by the phreatic surface near the eroded slope, and another in April (04/17/19), when this surface rises inside the slope. The lowest value persists during the dry season, influenced by delayed water table recharge. The highest safety factor occurs at the end of the dry season (10/08/18) when the water table is deeper again. The increase in the safety factor during the second half of January is a consequence of the dry spell (*veranico*).

The small variation in the safety factor may be a consequence of the lower rainfall of the year studied, which was approximately 82% of the local historical average (1348mm.y^{-1}). Slope undercutting during the dry season may also result in a decrease in the safety factor. However, stability analyses of the safety factor in this condition have not been done, as the forms of erosion at the slope base are very variable in space and time.

Therefore, it was possible to confirm two patterns of water percolation and aquifer recharge, which reflect the characteristics of the soils and the geometry of the gully slopes. On the portion of the natural slope, unaffected by the gully, the solum is more porous and permeable and water infiltrates more easily. However, it takes longer to recharge the aquifer at a depth of over 18 m due to the thick, relatively less permeable saprolite. In this section, the phreatic surface reaches its peak between July and August in the period of drought, confirming the findings of Drumond and Bacellar (2006), who found a 5-month lag time between the peak of the rain and the recharge of groundwater located 20 m deep.

Conversely, on the gully face, the saprolite emerges and the phreatic surface is shallower (<3 m), enabling faster recharge, especially when considering the rising capillary fringe which is high in this silty material. As a result of this distinct behavior, the safety factor is low at two different times: the peak of the wet season when the water table rises at the bottom of the slope, and the middle of the dry season when the water table rises inside the slope. In the rainy season, global slumps, involving the entire slope may occur, associated with others surface erosion processes (Fig. 7a). In the dry season slope undercut prevails because of the increase in the hydraulic gradient (Fig. 7b).

The rising hydraulic gradient at the toe of the slope is not sufficient to cause the static liquefaction of the saprolite but contributes to the decrease in the effective stress and, therefore, in the stability of the slope. However, the small slips observed on this stretch cause dynamic liquefaction, transforming them into smaller silt flow slides (Fig. 7b). The channelized flow through small discontinuities also generates small-scale piping erosion. All these mechanisms lead to the removal of slope-supporting soil in the dry season, facilitating global slump reactivation in the subsequent wet season.

Since the instability of these slopes is influenced by the groundwater regime, providing efficient drainage at the slope base is an effective means of stabilization. However, the difficult accessibility of the gully bottom and the high instability in this stretch, which is susceptible even to quicksand condition, makes it impossible to use most conventional slope stabilization methods, such as the installation of toe drains in trenches or horizontal drains (Abramson et al. 2001). Any excavation on this stretch is dangerous and may trigger a global rupture.

This work simulated a variation of the method proposed by Prandini et al. (1974) to stabilize a gully in a sandstone region. This involves the installation of alternative drains, which consists of throwing bags of soil-cement at the toe of the slope to work as a toe drain and its subsequent covering by a landfill. This variation includes a 2-m-high and 4-m-wide toe drain connected to a 0.5-m-thick subsurface drainage blanket (Figs. 7c and 8a). Note that unlike the solution of Prandini et al. (1974), a small excavation at the site of the toe drain is proposed, due to the difference in the geometry of the gully slope that would not allow the launch of the soil-cement bags from the ridge to the final site. It is complemented by a retaining wall designed with gabions and connected to the drainage blanket. It is completed with a landfill in 2.5:3 slope benches, with material from the slope, thus achieving greater economy and speed in execution. Except for the gabion screens, all other materials can be obtained locally and executed by unskilled labor, reducing costs. The recommended time to build this structure is at the end of the dry season, when the slope is more drained and more stable.

The slope safety factor was raised to values of approximately 1.32 (Fig. 8b) in this configuration, thus ensuring gully stability. This passive containment method makes it possible to reduce exfiltration at the toe of the gully (Fig. 8a), also reducing the undercutting caused by subsurface flows and reducing the fast water table recharge on the face of the gully. It is also possible to notice the change in the most critical rupture surface, making it more superficial, located above the water table, and of much smaller volume than in the natural condition (Fig. 8b). For complete stabilization, it is recomended to continue with the control of surface runoff.

Therefore, this is a feasible and low-cost solution to stabilize the slopes and prevent gullies from expanding. This is of great importance to the region, which has suffered severe economic, social, and environmental impacts because of the accelerated evolution of hundreds of gullies.

5. Conclusion

The Bação Complex region is one of the most affected by channeled erosion in Brazil. These erosion features begin with the concentration of surface waters, forming ravines, but when the groundwater at the base of the saprolite is reached, the processes of subsurface erosion begin, giving rise to gullies. For this reason, the usual practice of controlling surface runoff by terracing in contour lines has proven ineffective in stabilizing the hundreds of gullies in the region. Among the processes of subsurface erosion are the mass movements, especially the slumps.

The climate in the region is seasonal, with 5 to 6 months of rainy season alternating with months of low rainfall. The monitoring of these gullies along the hydrologic year indicates that slumps occur not only in the rainy season but also in the middle of the dry season. This phenomenon can be explained by the slow elevation of the water table because of the recharge, delayed to the rainfall peak. To verify this possibility, a representative gully with unstable slopes in the southeast of the Bação Complex was selected. The numerical simulations of saturated and unsaturated flow on one of the slopes of this gully for a hydrological year, showed that the water table presents seasonal fluctuations, with a maximum five to six months' delay in relation to the peak of the rainy season. This recharge delay is caused by the low percolation speed through the thick unsaturated zone, largely formed by the saprolite of silty texture. On the eroded stretch of the slope, where the unsaturated zone is shallower, the phreatic surface responds more quickly to rainy events. There is also strong upward flow at the toe of the slope throughout the year, with greater intensity in the drought season. These gradients explain the erosive processes that undercut the slope in the dry season, like boiling, piping erosion, creep, and flow slides.

Stability analyses of this slope by limit-equilibrium with imports of flow simulation displayed a meta-stable situation, with low safety factor values, with little variation throughout the hydrological year. The safety factor is lower in the rainy season due to the rapid saturation of the toe of the slope and then decreases again in the middle of the dry season, when the aquifer is recharged more slowly on the rest of the slope.

These data confirm that the stabilization of these erosive features can be achieved by the improvement of the water exfiltration condition at the toe of the gully. However, conventional stabilization measures are difficult and costly, due to the unstable conditions and the difficulty of access the base of these gullies. Therefore, a procedure to stabilize the slopes was simulated, with an alternative drainage system and gabion walls, which resulted in a significant gain in the safety factor.

The control of the evolution of hundreds of large gullies in the region is an issue of great importance because of the high social, economic, and environmental impacts they cause. Therefore, the proposition of a low-cost stabilization method for easy implementation is a major issue for regional sustainable development.

Declarations

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Conflict of interest:

We declare that there are no conflicts of interest associated with this research. The study is original and has not been submitted to any other journal.

Availability of data and material:

All data used in this work were obtained from government agencies (CEMADEN, INMET) or sourced from previous studies as mentioned.

Code availability:

Availability of Geostudio 2020 software, version 10.2.1.19666.

Authors' contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yesser Marin Rodriguez Hernandez and Luis de Almeida Prado Bacellar. The first draft of the manuscript was written by Yesser Marin Rodriguez Hernandez and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

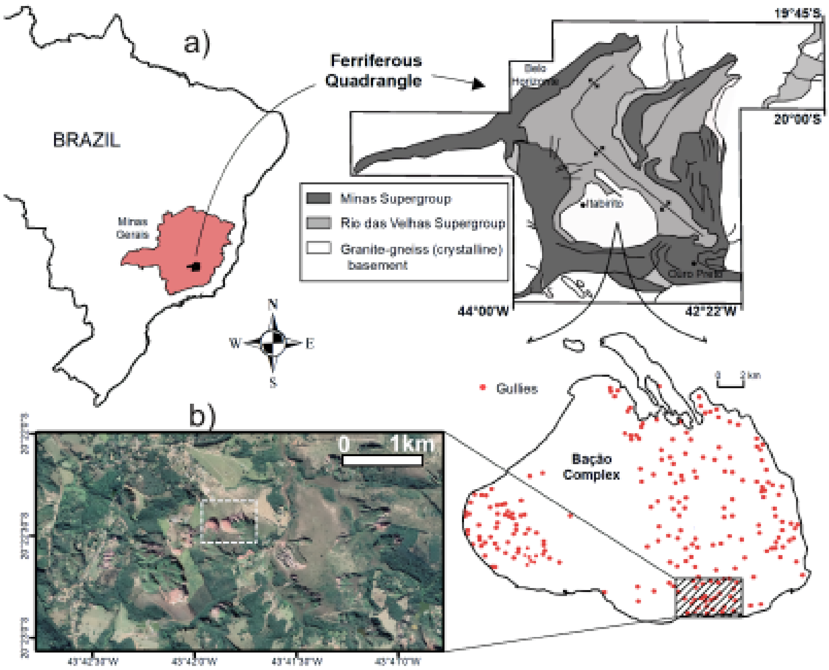

Figure 1

a) Location of Bação Complex in the Ferriferous Quadrangle, southeastern Brazil; b) Right: distribution of gullies in the Bação Complex, and (left) satellite image (Source: Google Earth) of the region, with the study area indicated, in the Holland monitoring station Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

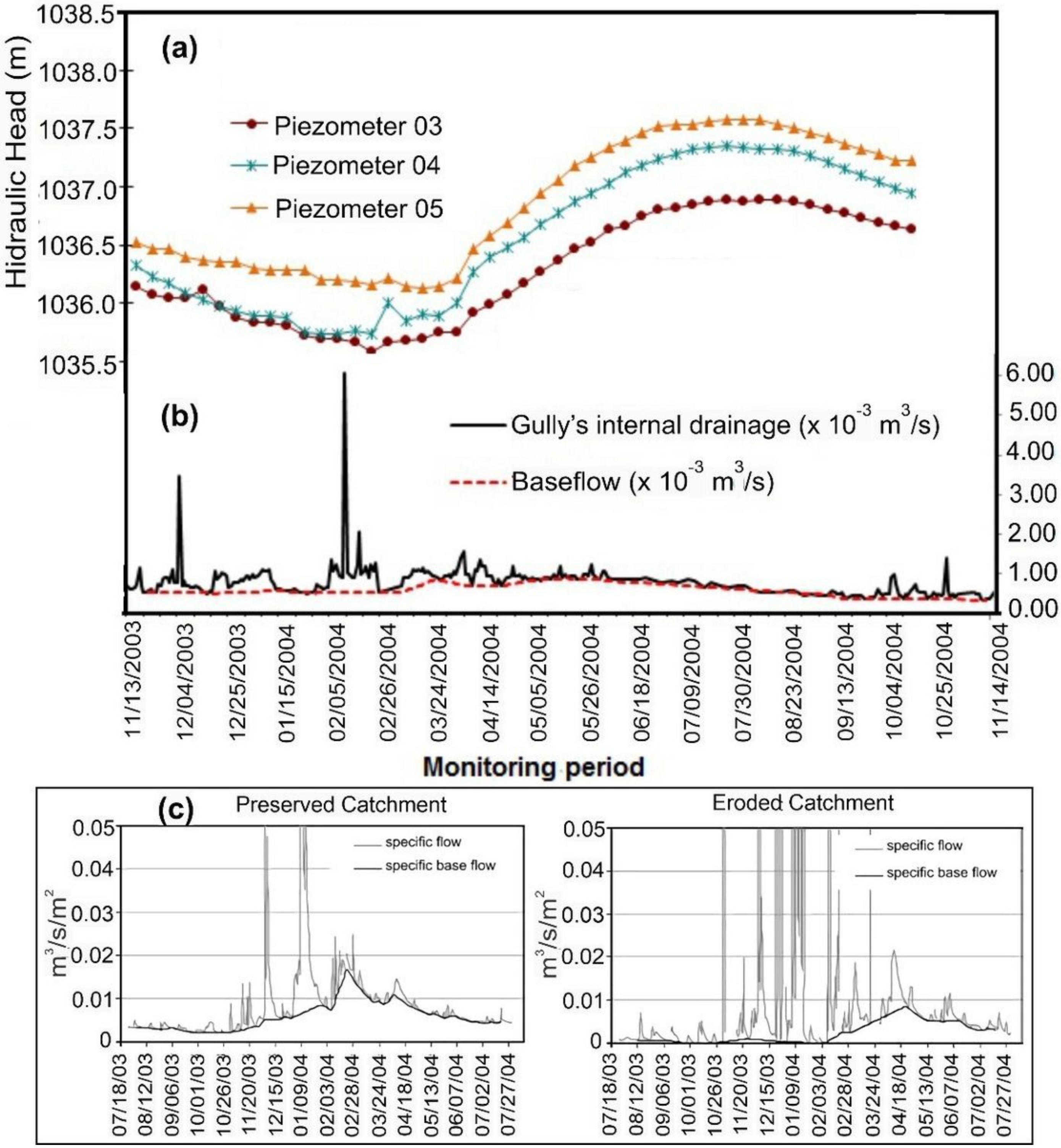

Figure 2

Hydrological behavior of the region. a) Variation in the water level (hydraulic head) of three piezometers located upstream of Mangue Seco gully. b) Hydrograph of the drainage channel at the watershed mouth of Mangue Seco gully (scale on the right). Note that the base flow rises after the rainy season (adapted from Lima et al 2018). c) Hydrographs of daily flows of two catchments in the vicinity of the area. Note that the base flow increases at the end of the rainy season and lasts until April/May in the dry season (adapted from Costa and Bacellar 2007)

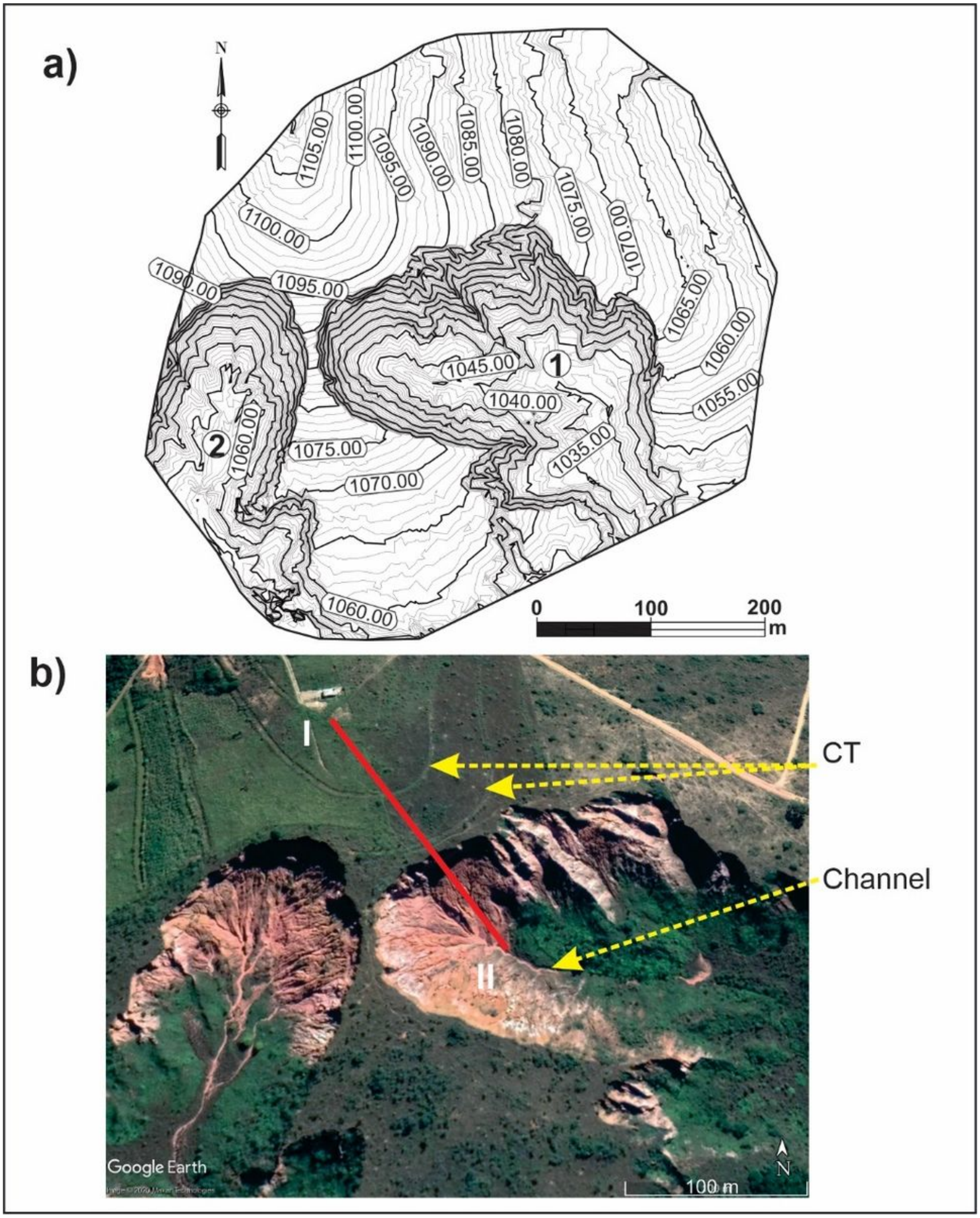

Figure 3

a) Topographical map of the area of the Holland monitoring station, with the location of the studied gully (1). b) Satellite image of the area obtained on 05/31/2019 (Google Earth), with the location of the analyzed section (in red), the contoured terraces (CT) for surface erosion control, and the internal channel formed by the effluent flow at the toe of the slopes. The unstable gully slopes are those devoid of vegetation Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

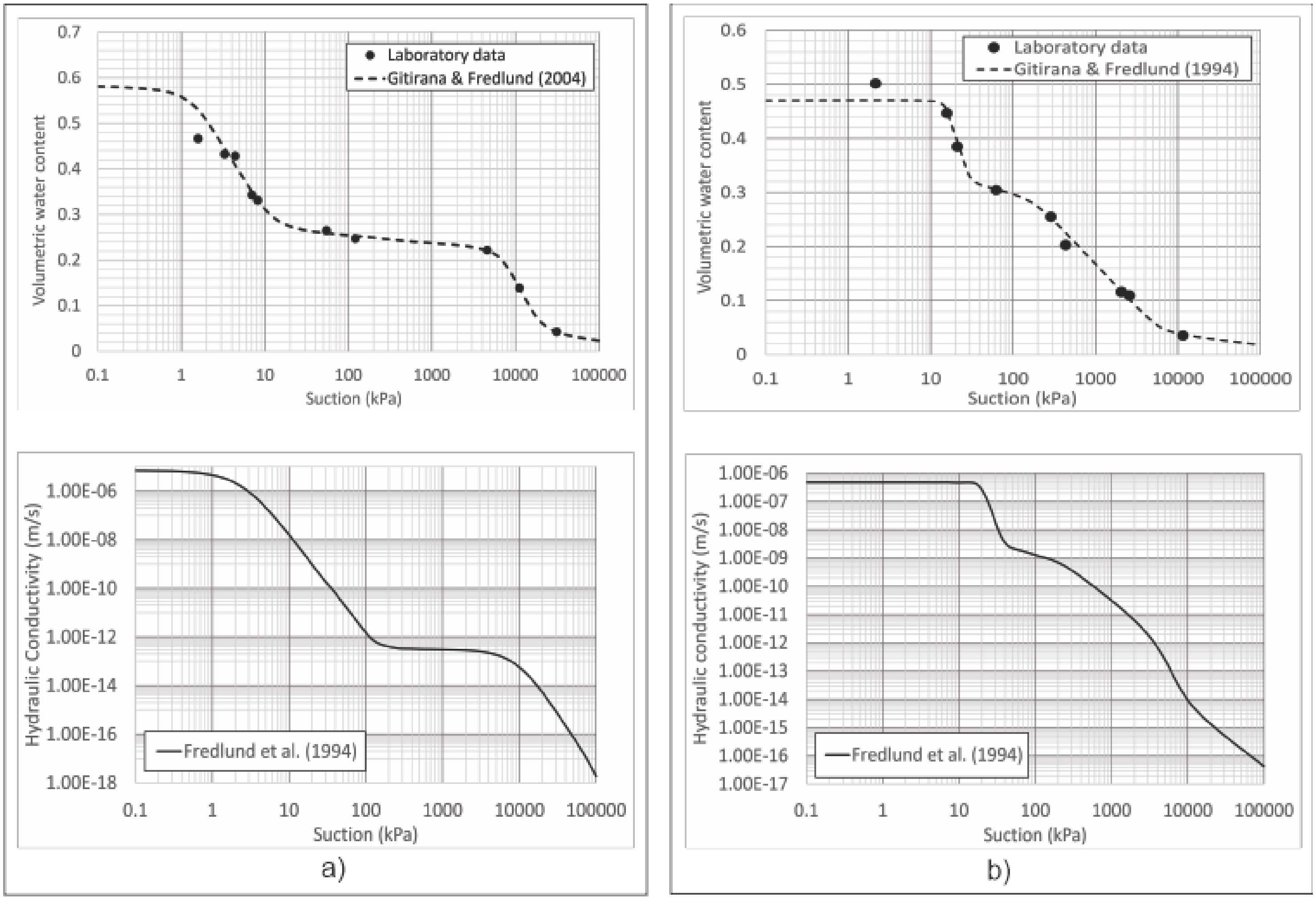

Figure 4

Retention curves and unsaturated hydraulic conductivity function. Note bimodal behavior of soils (a) Solum (Bw horizon); (b) Saprolite (C Horizon)

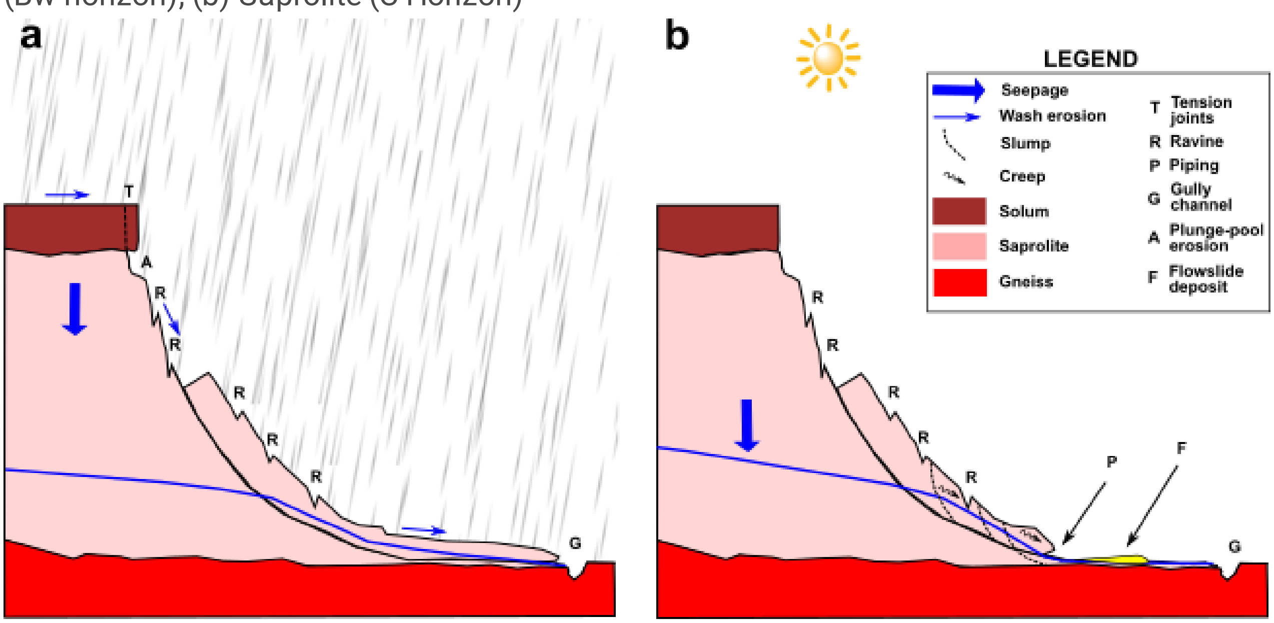

Figure 5

Erosion mechanisms acting in gullies: a) in the wet season; b) in the dry season, when the delayed recharge occurs, raising the water table and undermining the base of the slope

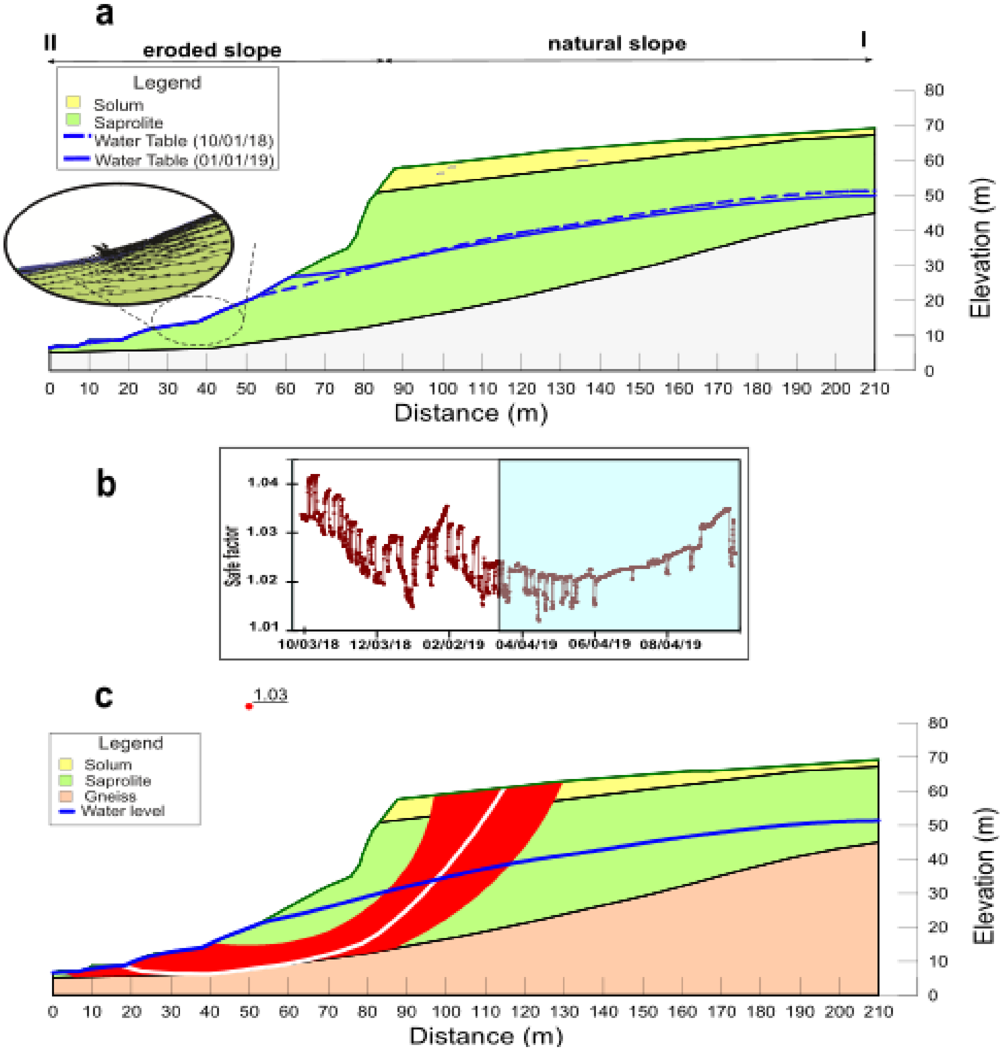

Figure 6

a) Simulated geological cross-section (location in Figure 3), illustrating the position of the water table at the beginning of the simulation 10/01/2018 at the end of the dry season (dashed line), and on 01/01/2019 in the rainy season. The water table rises most in the eroded sector of the slope in the rainy season because of the thinner unsaturated zone. The detail shows the upward flow components that occur throughout the year at the toe of the slope. b) Variation in the safety factor over the hydrological year. The dry period is marked with a blue rectangle. Note that the average safety factor is low at the beginning of the dry season, when the water table is high, and gradually rises in subsequent months. c) Slump rupture surface (in white) at the beginning of the hydrological year (10/01/18) and the potential zone of rupture (in red).

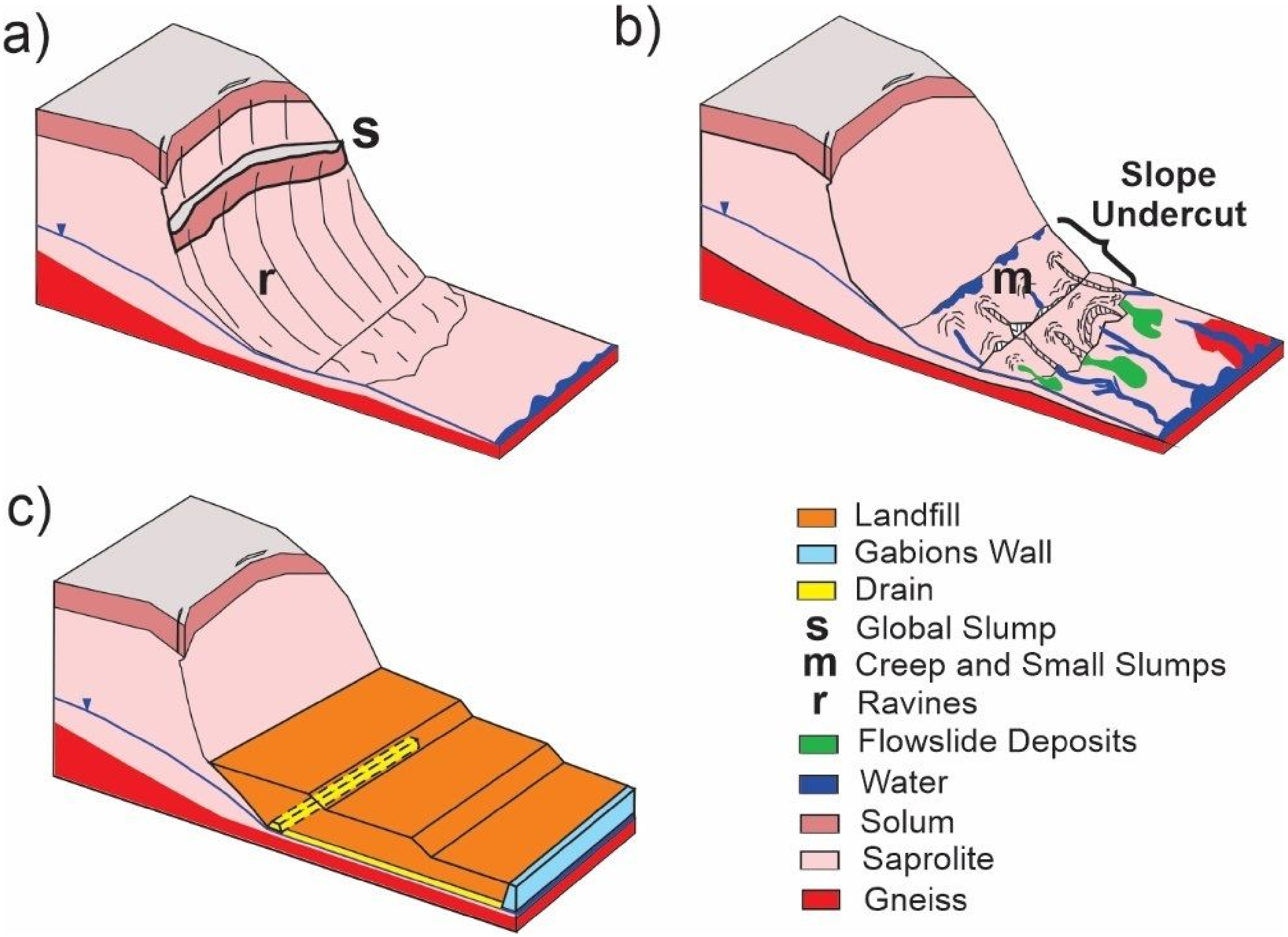

Figure 7

a) Erosion process operating on the slopes of the gullies. a) In the rainy season, global slumps, involving the entire slope may occur, associated with others surface erosion processes such as plunge-pool erosion, sheet erosion, and ravines; (b) in the dry season, as a result of delayed water tabel recharge, several mechanisms can act by undercutting the slope base, preparing for further overall slippage in the subsequent rainy season. c) proposal of slope stability solution, with the construction of toe and blanket drains and landfill, from the slope benching (not shown in the picture)

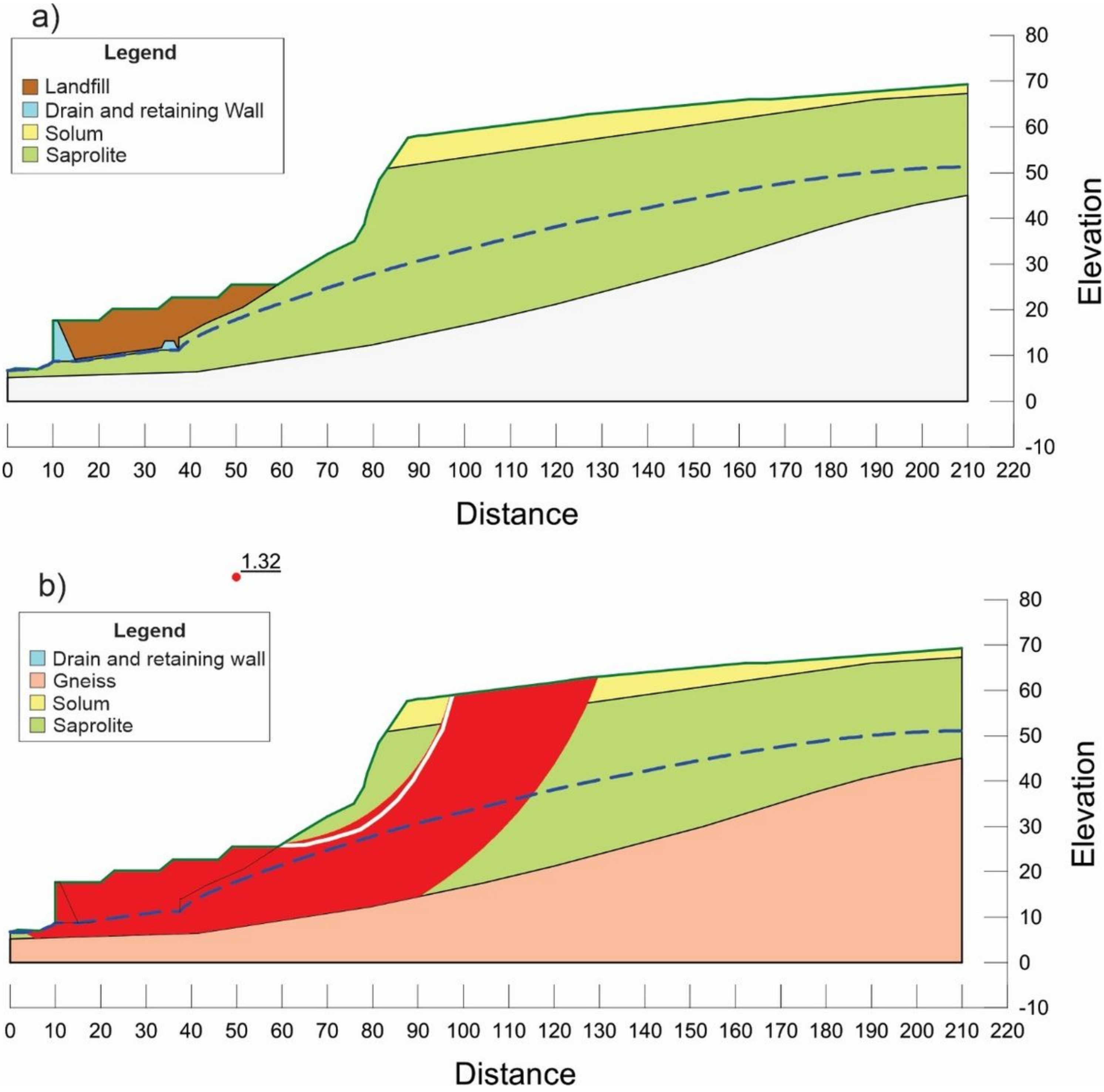

Figure 8

a) Flow numerical model of the solution proposal with toe and blanket drains and landfill. b) Rupture surface (white line) and potential rupture zone (in red), of the solution proposal