Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Use of the MUSLE equation calibrated with drone images to analyze sediment dynamics in a mining area

ARTICLES doi:10.4136/ambi-agua.3110

Received: 16 Aug. 2025; Accepted: 06 Mar. 2026

Luisa da Cunha Vieira[1*]; Lucas Fontanetti Martins[2]; José Carlos de Melo Bernardino[2]; Lívia Jacobini[3]; Gabriel Rezende Coelho[4]

[1]Gerência de Projetos Geotécnicos. BVP Geotecnia e Hidrotecnia, Rua Tomé de Souza, n° 616, CEP: 30140-131, Belo Horizonte, MG, Brazil.
[2]Centro Tecnológico de Hidráulica. Departamento de Engenharia Hidráulica e Ambiental. Escola Politécnica da Universidade de São Paulo (Poli-USP), Avenida Professor Lucio Martins Rodrigues, n° 120, CEP: 05508-020, São Paulo, SP, Brazil. E-mail: lucas.fontanetti.martins@usp.br, jcarlosmbernardino@usp.br
[3]Gerência de Projetos Estruturantes. Samarco, Avenida Getúlio Vargas, n° 671, CEP: 30112-021, Belo Horizonte, MG, Brazil. E-mail: livia.jacobini@samprojetos.com
[4]Gerência de Geotecnia. Samarco, Avenida Getúlio Vargas, n° 671, CEP: 30112-021, Belo Horizonte, MG, Brazil. E-mail: gabriel.coelho@samarco.com
[*]Corresponding author. E-mail: luisadacunhavieira@gmail.com

Editor-in-Chief: Nelson Wellausen Dias

ABSTRACT

In mining environments, erosion and sediment transport can generate significant downstream impacts. A comprehensive understanding of these processes is therefore essential for designing effective control and mitigation strategies. This study examined sediment deposition dynamics in drainage channels within a mining area during a single rainfall event. The Modified Universal Soil Loss Equation (MUSLE), calibrated with drone-based photogrammetric data, was applied to estimate sediment yield in sub-basins of the Germano Dam catchment (Mariana, Minas Gerais), currently undergoing decommissioning. Surface runoff and sediment discharge were incorporated into a two-dimensional hydrodynamic model (RiverFlow2D®) to simulate flood routing and bedload transport throughout the channel network. Results indicated minimal sediment deposition during the 2-year return period event, except in the Chico Basin channels, where sediment input from the Germano Pit promoted accumulation. Overall, the study highlights the potential of integrating empirical models, numerical simulations, and geospatial technologies to assess siltation in hydraulic systems in mining areas, particularly under conditions where in situ monitoring is limited.

Keywords: mining, MUSLE, sediment transport.

Utilização da equação MUSLE calibrada por meio de imagens de drone para análise da dinâmica de sedimentos em área de mineração

RESUMO

Na mineração, a erosão e o transporte de sedimentos podem gerar impactos significativos em regiões a jusante e, por isso, a compreensão da dinâmica desses fenômenos é fundamental para que sejam desenvolvidas medidas de controle e minimização nas áreas afetadas. Este trabalho analisou a dinâmica de deposição de sedimentos em canais de drenagem implantados em área de mineração, considerando um evento pluviométrico isolado. Para isso, foi utilizada a Equação Universal de Perda de Solos Modificada (MUSLE), calibrada a partir de dados obtidos por levantamentos aerofotogramétricos com drone, como forma de estimar a produção de sedimentos em sub-bacias da área de contribuição da Barragem do Germano (Mariana-MG), atualmente em processo de descaracterização. As vazões líquidas e sólidas foram integradas a um modelo hidrodinâmico bidimensional (RiverFlow2D®, permitindo simular o trânsito da cheia e o transporte de carga de fundo no sistema de canais. Os resultados indicaram baixa tendência geral de deposição de sedimentos para o evento analisado (Tempo de Retorno de 2 anos), com destaque para acúmulo significativo nos canais da Bacia do Chico, área que atualmente recebe aporte expressivo da Cava do Germano. O trabalho aponta para o potencial de integração de diferentes ferramentas - modelagem empírica, simulação numérica e geotecnologias - na análise do assoreamento em sistemas hidráulicos de áreas mineradas diante da carência de dados medidos *in situ*.

Palavras-chave: mineração, MUSLE, transporte de sedimentos.

1. INTRODUCTION

Erosion and sediment transport processes directly influence the functioning of riverine and channel systems, leading to geomorphological changes in the riverbed, degradation of water quality, siltation, and blockages – ultimately increasing the risk of flooding and overtopping, among other impacts (Silva *et al.*, 2024). Understanding these processes is therefore essential for developing effective control and mitigation strategies.

Although naturally occurring – such as through the action of water, wind, and gravity – these processes may be intensified by anthropogenic activities (García, 2007). In mining operations, vegetation removal coupled with extensive earthmoving activities makes the soil highly susceptible to accelerated erosion. In the absence of proper control measures, part of this material can be transported by surface runoff, negatively affecting downstream areas.

Mathematical models of sediment transport have been employed to represent the physical processes governing erosion, transport, and deposition of particles (Jiang *et al.*, 2025). These models consider factors such as flow dynamics (velocity, depth, and turbulence patterns), sediment properties (size, density, and grain size distribution), and flow–sediment interactions (sedimentation rate and incipient motion criteria). For these models to produce representative and reliable results, they must be parameterized or calibrated using in situ data.

In mining areas, sediment generation typically occurs at high intensities over short periods, and sediment characteristics may vary significantly. However, in situ monitoring is often hindered by ongoing construction activities and restricted access to sampling points during rainfall events, due to lightning alerts that require site evacuation. Additionally, these basins are generally small, with short response times, often precluding monitoring teams from reaching sampling sites during peak flows.

Given these constraints and the persistent lack of hydrosedimentological monitoring, it has become common practice to adopt sediment yield estimates ranging from 300 $m^3\ ha^{-1}\ year^{-1}$ to 600 $m^3\ ha^{-1}\ year^{-1}$ (USEPA, 1976). The use of models such as the Universal Soil Loss Equation (USLE) has demonstrated that such values are appropriate for annual estimates in mining areas (Brito *et al.*, 2022; Gomes, 2012). However, references that specifically address sediment generation associated with isolated rainfall events in mining areas remain scarce.

The Modified Universal Soil Loss Equation (MUSLE) has been widely used to estimate soil loss and sediment yield associated with individual rainfall–runoff events in basins under diverse environmental conditions (Machado *et al.*, 2009; Mantovani *et al.*, 2018; Nunes *et al.*, 2022). Derived from the USLE, originally developed for agricultural applications (Carvalho, 2008), the MUSLE was designed to calculate soil loss for specific surface runoff events, incorporating the energy associated with runoff rather than relying solely on rainfall energy, as in the original USLE (Kinnell and Risse, 1998). This modification makes the MUSLE more suitable for short-term erosion events and for scenarios where surface runoff is a determining factor.

In light of the above, this study aims to qualitatively analyze sediment deposition dynamics associated with an isolated rainfall event in a channel system located within a mining area. For this purpose, a mathematical model of sediment transport was employed, with sediment yield estimated using the MUSLE. Due to the absence of in situ monitoring data, the model was parameterized using estimated sediment detachment values derived from the MUSLE calibrated with data obtained from drone imagery.

2. MATERIAL AND METHODS

2.1. Study area context

The Germano Dam, owned by Samarco Mineração, is located in the municipality of Mariana, in the state of Minas Gerais (Brazil), and is undergoing a decommissioning process. This includes, among other actions, topographic regrading of the reservoir area and the area immediately upstream – known as the Chico Basin – to prevent the formation of a water body, and the construction of a drainage channel system designed to collect surface runoff from the dam's contributing basins and direct it downstream of the geotechnical structure. The embankment slopes are graded toward the drainage system, ensuring that all precipitation falling directly on the embankments is directed into the channels. Figure 1 shows the study area along with the layout of the decommissioning engineering design.

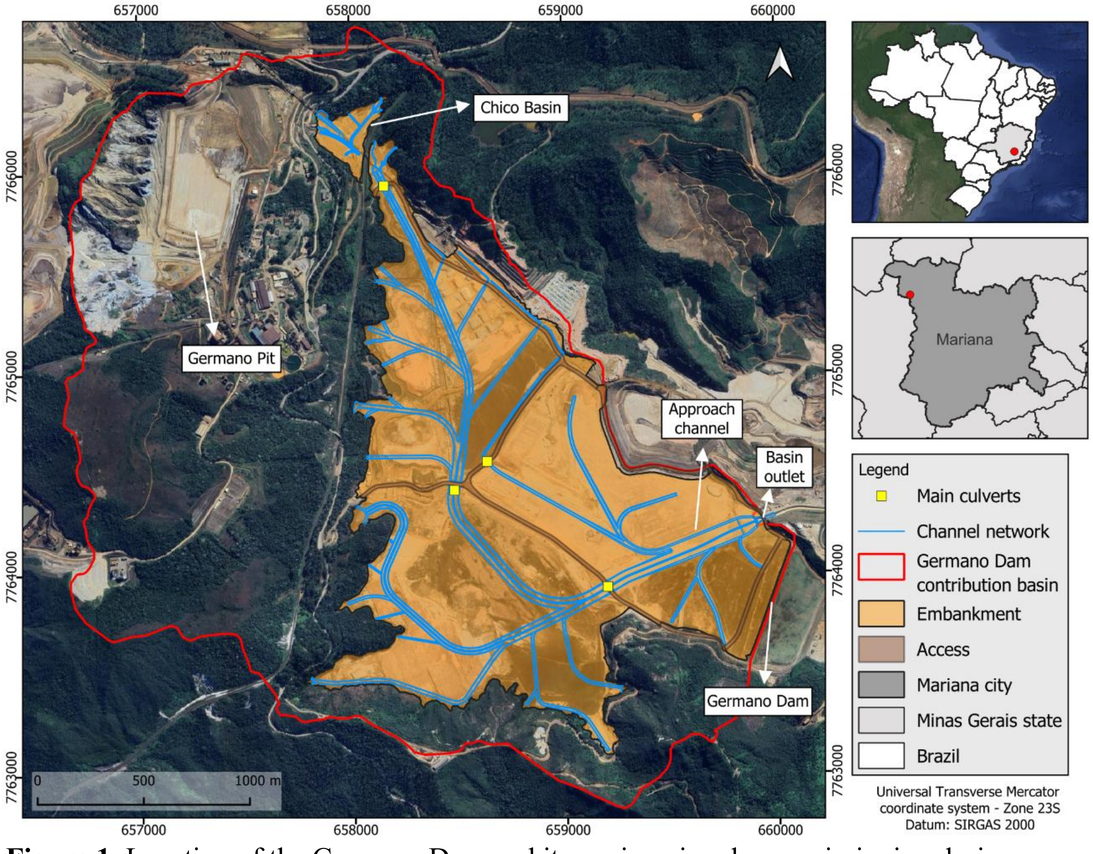

Figure 1. Location of the Germano Dam and its engineering decommissioning design.

The Germano Dam reservoir and Chico Basin channel system was designed to accommodate the peak flow associated with the Probable Maximum Precipitation (PMP). With a trapezoidal cross-section, the channels feature wide bases and gentle longitudinal slopes, which help reduce flow velocities.

2.2. Drone-derived data

As described in Section 2.3, part of the methodological procedure included the use of drone imagery for mapping the study area. All flights were conducted by the mining company, which also provided the operational flight parameters used in the preparation of this article.

For the generation of orthomosaics, a fixed-wing eBee Plus drone equipped with a high-resolution RGB camera model S.O.D.A. 10.6 was used. Flights were conducted following a regular grid pattern with parallel flight lines at an average altitude of approximately 120 m above the takeoff point, in compliance with current national regulations (ANAC, 2023; Brasil, 2023). This configuration resulted in a mean Ground Sampling Distance (GSD) of 8.0 cm/pixel.

The total surveyed area was approximately 3.33 km², with an average acquisition of 244 images per campaign. Mission planning and flight control were carried out using the eMotion software.

To ensure both planimetric and altimetric positional accuracy of the orthomosaic, the Post-Processed Kinematic (PPK) positioning technique was employed (Brasil, 2016; Santos *et al.*, 2016). The eMotion software was used for both flight planning and execution, including post-processing correction of image coordinates. Photogrammetric processing was performed using Pix4Dmapper, which applies the *Structure from Motion* (SfM) method for three-dimensional surface reconstruction (Magalhães and Moura, 2021).

Despite the spatial consistency of the obtained results, some inherent limitations of the technique must be considered. The camera viewing angle may affect reconstruction quality in areas with very steep slopes or near-vertical surfaces. Furthermore, the estimation of small mobilized volumes may approach the order of magnitude of the method's vertical accuracy, requiring caution when interpreting subtle volumetric variations (Magalhães, 2021).

2.3. Methodological sequence

To support the development of the Germano Dam decommissioning engineering design, hydrological and hydrodynamic simulations were previously conducted using the RiverFlow2D® model.

Developed by Hydronia LLC, RiverFlow2D® is a two-dimensional hydraulic model based on volume conservation, solving the shallow water equations derived from the vertical integration of the Navier–Stokes equations. It is also classified as a distributed hydrological model, as it accounts for the spatial variability of parameters in rainfall-runoff modeling, and enables integrated assessment of flow dynamics through a mesh composed of elements that incorporates factors such as ground surface elevation, precipitation, soil infiltration parameters, and flow resistance coefficients. The mesh may also include hydraulic structures such as channels, culverts, and bridges. RiverFlow2D® includes eight modules, one of which is dedicated to sediment transport modeling.

In this context, the coupled hydrological–hydraulic model enabled the simulation of flood routing within the Germano Dam contributing basin, as well as flood propagation through the designed drainage channel system. Given the substantial sediment yield expected from the basin and the low slope of the channels, it became relevant to assess the hydraulic performance of the surface drainage system while incorporating sediment transport effects.

The study was structured into four main stages, as illustrated in Figure 2.

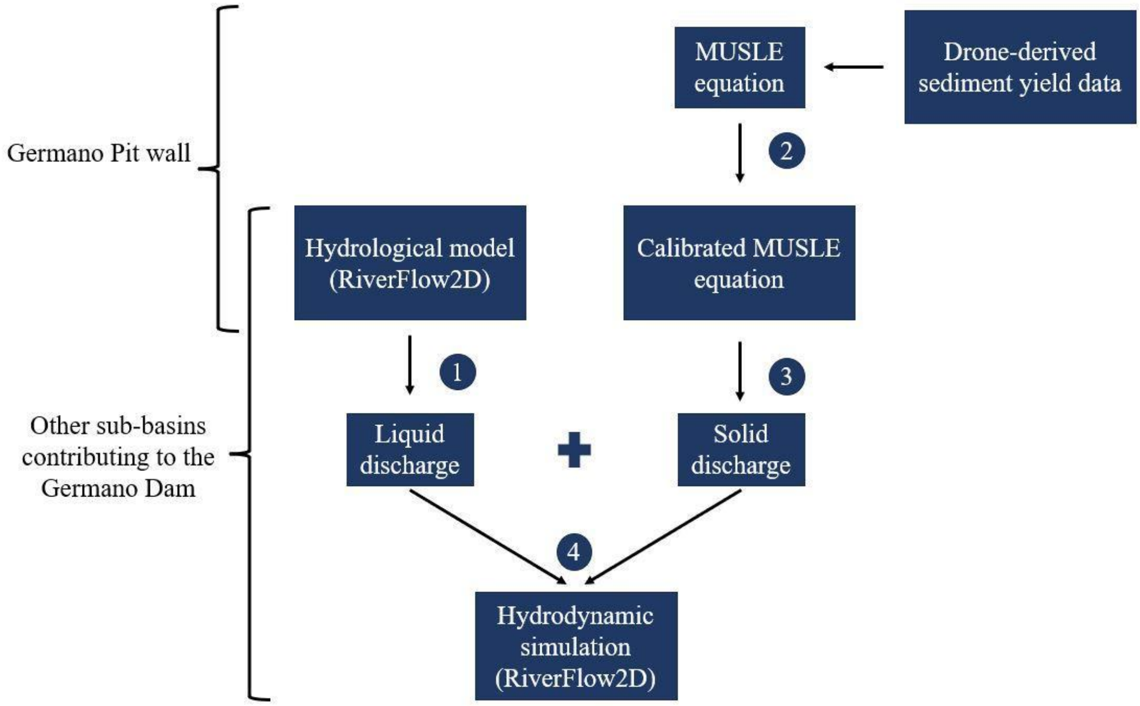

Figure 2. Flowchart of the study methodology.

Step 1: the liquid discharges were obtained from the hydrological model employed in the executive design project for the Germano Dam decommissioning. A 2-year return period was adopted, representing more frequent flood events and, therefore, those with greater potential to cause sediment accumulation within the surface drainage channels. The critical duration (4-h) of the 2-year return period event was considered for the Germano Dam catchment. This means that, for a 2-year event, the 4-h duration produces the highest peak discharge at the basin outlet.

The model used a 1-minute time step and simulated an 8-h rainfall–runoff event. As a result of the hydrological simulation performed in Step 1, hydrographs were generated for all sub-basins represented in Figure 3. These hydrographs were then used as upstream boundary conditions in the model implemented in Step 4.

Step 2: between January 2021 and January 2023, four drone-based aerial photogrammetric surveys were conducted on the Germano Pit wall. These surveys made it possible to estimate the volume of sediment detached between each acquisition date. This volume was also estimated using the Modified Universal Soil Loss Equation (MUSLE), represented by Equation 1:

$$Y = 11{,}8\,.\,(Q\,.\,q_p)^{0{,}56}.\,K.\,LS.\,C.\,P \quad (1)$$

Where: Y is the estimated soil loss (sediment yield) from a rainfall event (in tons); Q is the runoff volume from the rainfall event (in m³); q_p is the peak runoff rate (in m³/s); K is the soil erodibility factor; LS is the topographic factor, accounting for slope length and steepness; C is the crop management factor; P is the support practice factor.

The MUSLE was then calibrated to determine an appropriate empirical coefficient (in place of the default value of 11.8) that would yield sediment accumulation estimates consistent with those observed in the drone-based surveys, thereby adapting the equation to the specific conditions of the study area.

Step 3: The MUSLE equation calibrated in Step 2 was then applied to estimate the solid discharge from the remaining sub-basins contributing to the channel system (Figure 3).

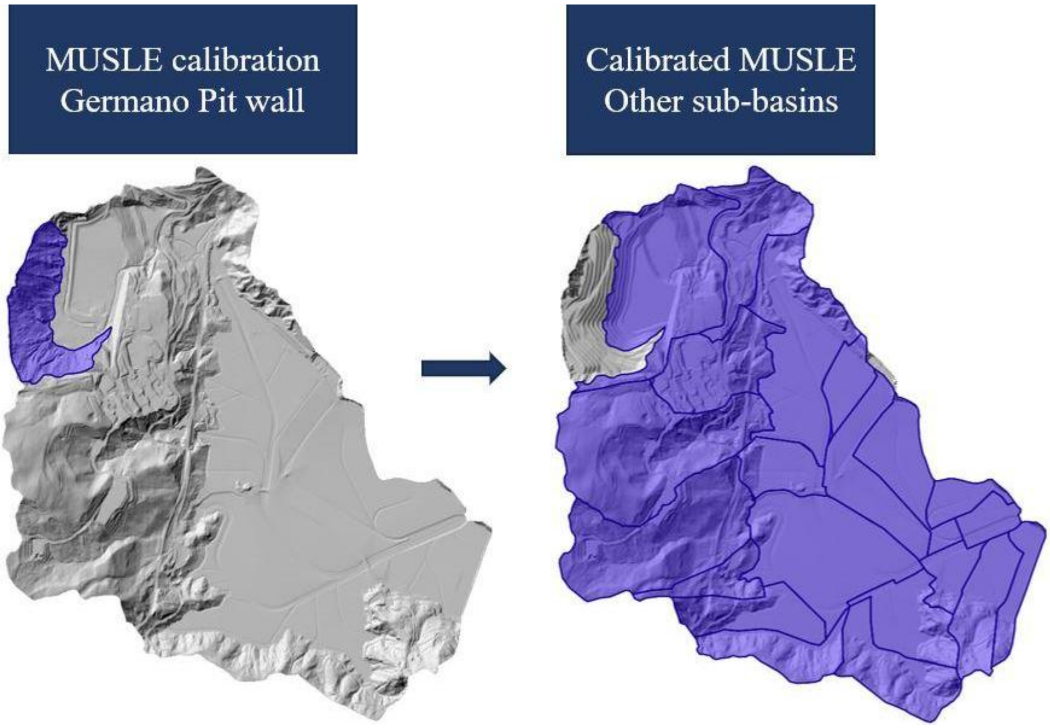

Figure 3. Schematic representation of the calibrated MUSLE application and the sub-basins considered.

Each parameter of the MUSLE was determined following the approach adopted by Nunes *et al.* (2022), based on the original formulation proposed by Williams (1975), as detailed below.

The empirical coefficient was calibrated to a value of 6.30, replacing the original default value of 11.8; runoff volume (Q) was calculated by multiplying the area of each sub-basin by the effective precipitation determined by the NRCS method; peak discharge (qp) was obtained by multiplying the area of each sub-basin by the effective precipitation and dividing the result by the time to peak of the hydrograph, which corresponds to 60% of the time of concentration. The time of concentration was calculated using the equation proposed by Watt and Chow (1985), as cited in Nunes *et al.* (2022), based on the length of the main channel and the average slope of the sub-basins; K factor was determined according to hydrologic soil groups, based on Nunes *et al.* (2022); CP factor (C × P) was derived from the land use types and hydrologic soil groups, following Nunes *et al.* (2022); LS factor represents the topographic factor and was calculated using the “LS factor” algorithm available in the SAGA plugin of QGIS.

After calculating soil loss for each sub-basin, it was necessary to apply an adjustment factor to ensure that the sediment volume produced by a discrete rainfall event would match the total sediment volume estimated for the same event over time.

As a result of applying the MUSLE in Step 3, solid discharge hydrographs were generated for all sub-basins represented in Figure 3. These were subsequently used, along with the liquid discharge hydrographs, as upstream boundary conditions in the model developed in Step 4.

Step 4: a hydrodynamic simulation of flow through the channels was carried out using the sediment transport module of the RiverFlow2D® model. The computational mesh was restricted to the channel boundaries, as shown in Figure 4(a).

For the upstream boundary condition, several channel inlets were defined, to which the liquid and solid discharge hydrographs were assigned for each sub-basin shown in Figure 3. For the downstream boundary condition, the rating curve of the channel located at the outlet of the Germano Dam basin was applied. The configuration of hydraulic structures and soil roughness parameters was defined based on the hydrological model from Step 1.

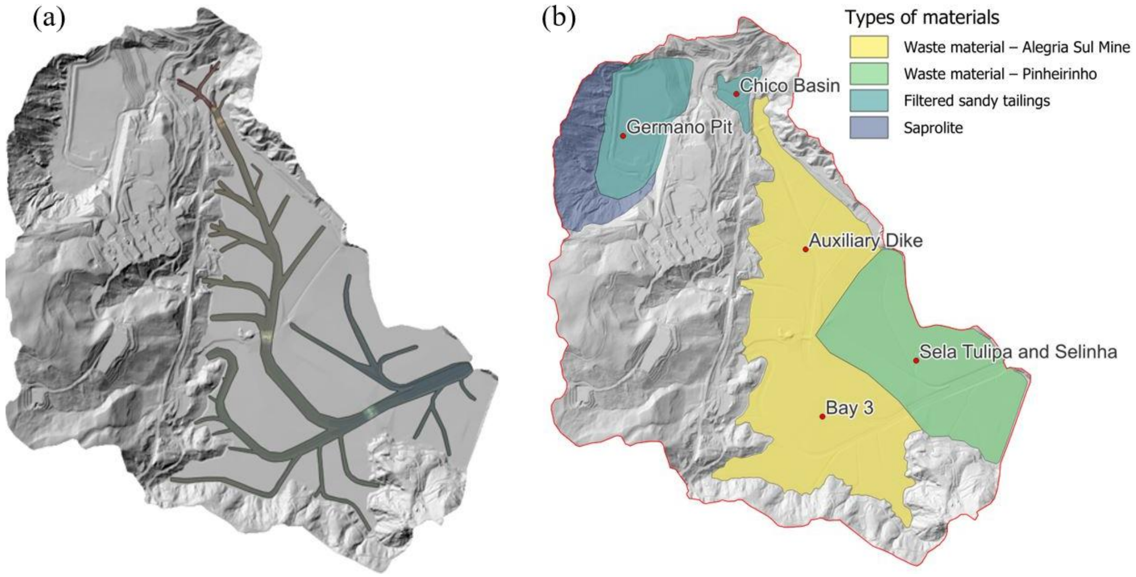

Figure 4. Computational mesh used in the hydrodynamic simulation (a) and cover materials (b).

2.4. Sediment transport model

Sediment transport is commonly classified based on the transport mode: bed load refers to the movement of larger particles that roll, slide, or bounce along the channel bed due to the force of the flow, while suspended load involves finer particles, such as silt and clay, that remain suspended within the water column. In this study, bed load transport was evaluated, as it represents the sediment fraction with the greatest potential for deposition within the channel system. Among the various sediment transport equations available in RiverFlow2D®, the Meyer-Peter & Müller (MPM) equation, developed in 1948, was selected. The MPM formulation is one of the most widely used for estimating bed load transport (Kuriqi *et al.*, 2019; Sidiropoulos *et al.*, 2021). It is based on the concept of shear stress and assumes that sediment transport occurs when the shear stress exerted by flowing water on the bed exceeds a critical threshold. The MPM formulation is expressed according to Equation 2.

$$q_b = k\,.\,(\tau - \tau_c)^{1,5} \quad (2)$$

Where: q_b is the bed load transport rate (sediment discharge per unit width); τ is the shear stress exerted by flowing water on the bed; τ_c is the critical shear stress required to initiate sediment motion (calculated using the Shields parameter); and k is an empirical coefficient.

This formula is particularly applicable to sandy and gravelly sediments under conditions of uniform flow (Meyer-Peter and Müller, 1948), which corresponds to the predominant sediment characteristics observed in the Germano Dam and Chico Basin channel system.

To solve the sediment transport equation implemented in the RiverFlow2D® model, it is necessary to define the geotechnical parameters for each type of surface material present within the drainage system's area of influence and contributing zone. These parameters were determined based on existing laboratory test data. The different types of materials considered are illustrated in Figure 4(b) and include: Germano Pit: natural terrain composed of saprolite along the pit walls, and filtered sandy tailings deposited both within the pit and along the embankments; Chico Basin: filtered sandy tailings used in embankments and waste material from adjacent area (Pinheirinho); Germano Dam reservoir: waste material sourced from Alegria Sul Mine applied in the Auxiliary Dike and Bay 3, as well as material from Pinheirinho excavation, used in the areas of Sela Tulipa and Selinha; adjacent areas to the above structures: Pinheirinho waste material, as these natural terrains are geologically similar to the Pinheirinho region.

The parameters adopted for each sediment type are listed in Table 1. Due to the variability of laboratory results for each material, average values were used in the model. For the Shields parameter (critical shear stress coefficient), the model's default value of 0.047 was retained.

Table 1. Geotechnical parameters for each sediment type.

Parameters/ Sediment type	Class 1	Class 2	Class 3	Class 4	Class 5
	Filtered sandy tailings	Saprolite R0	Saprolite R1	Alegria Sul Mine waste	Pinheirinho waste
Mass density (kg m-3)	2,750	3,060	2,960	3,300	2,900
D_{50} (mm)	0.052 – 0.075	0.01 – 0.05	0.045 – 0.15	0.06 – 0.9	0.011 – 0.72
Porosity	0.33 – 0.41	0.33 – 0.42	0.25 – 0.49	0.35 – 0.41	0.44 – 0.55
Shields parameter	0.047	0.047	0.047	0.047	0.047
Friction angle (°)	32	23	24	31	30

3. RESULTS AND DISCUSSION

3.1. MUSLE calibration

The MUSLE was calibrated to determine an appropriate multiplicative factor (replacing the original 11.8) that would yield sediment detachment estimates from the Germano Pit wall consistent with drone-based photogrammetry surveys, thus adapting the equation to the study area conditions. The calibration process resulted in a factor of 6.30, with a percent error of about -0.24%. This calibrated factor was subsequently applied in the MUSLE to estimate sediment yield in the other sub-basins that contribute to the drainage channels. Table 2 shows the values of remaining slipped and transported material mapped by drone surveys, and those computed using both the uncalibrated and calibrated MUSLE.

Table 2. MUSLE calibration results for the Germano Pit wall.

Date	Remaining slipped and transported material		
	Drone	Multiplicative factor 11.8	Multiplicative factor 6.3
3/23/2022	385,900	950,750	507,600
7/27/2022	412,420	986,290	526,580
1/17/2023	1,029,390	1,477,940	789,070
Sum	1,827,710	3,414,980	1,823,250
Error		86.84%	-0.24%

3.2. Flow and sediment dynamics

Using the liquid discharge hydrographs, along with the MUSLE calibration and the resulting solid discharge hydrographs for the sub-basins of interest, a hydrodynamic simulation of sediment transport was carried out in the channels.

Figures 5 and 6 present the maps of maximum flow velocity and maximum flow depth, respectively, within the channel system.

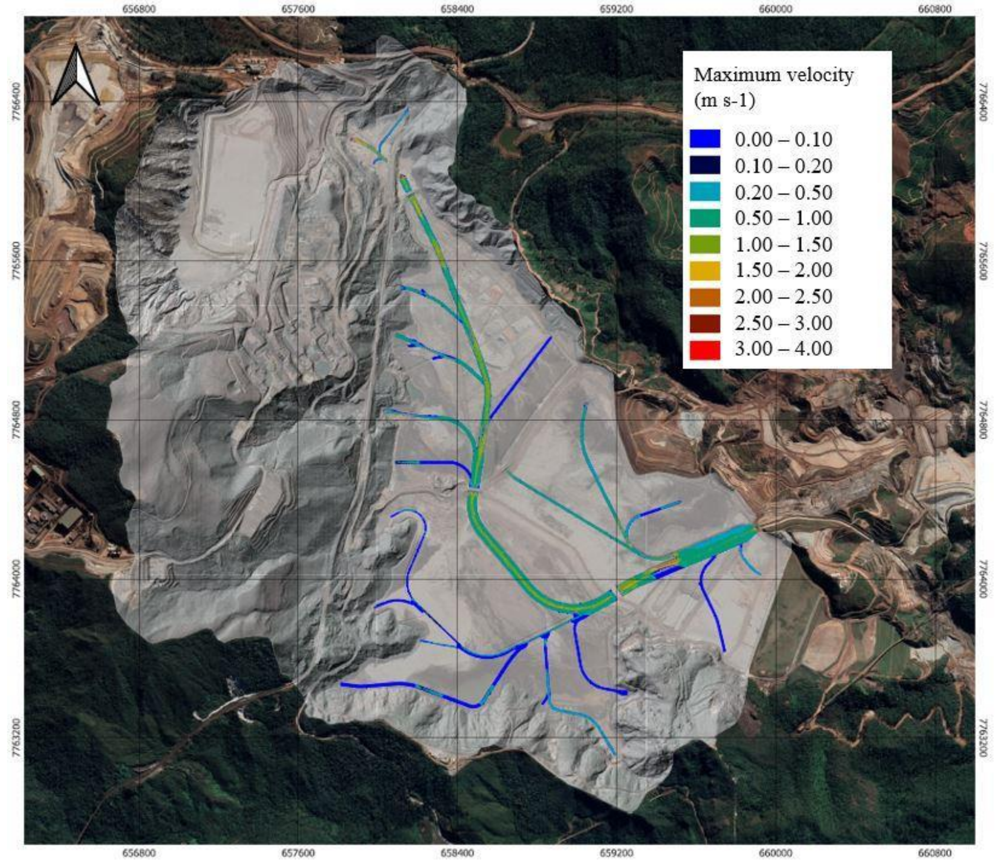

Figure 5. Maximum flow velocity within the drainage channels.

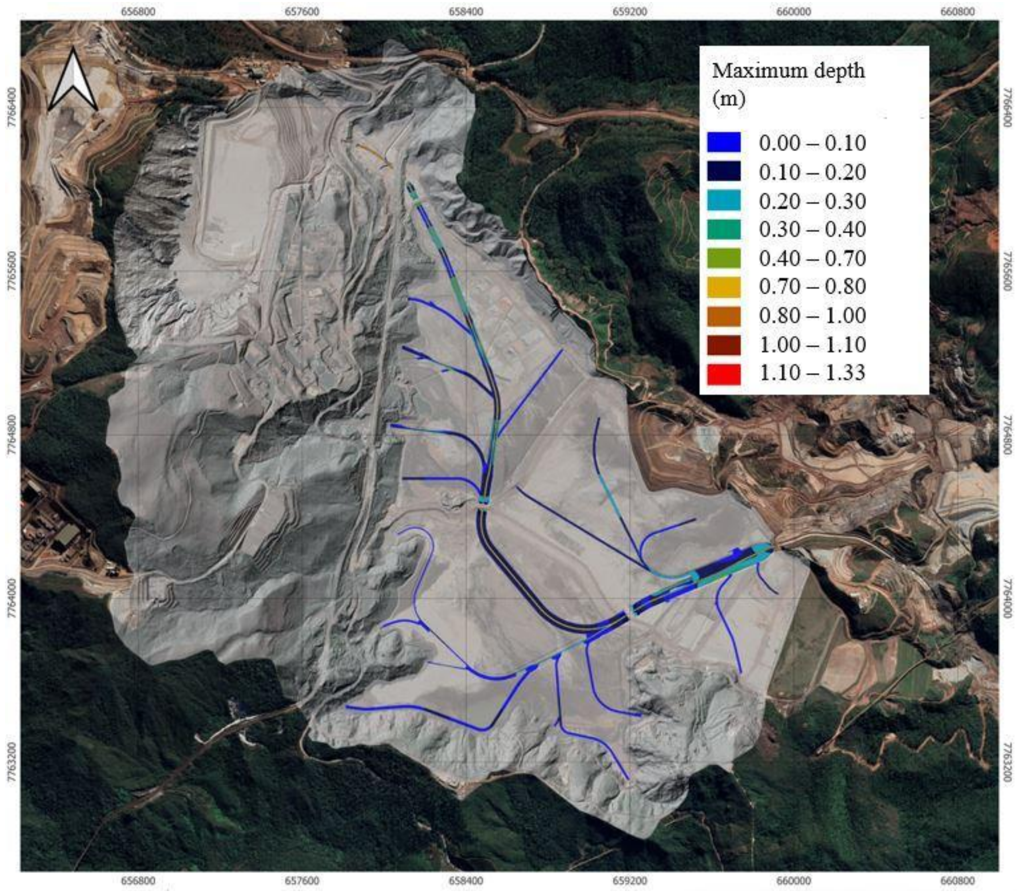

Figure 6. Maximum flow depth within the drainage channels.

The inflow discharges used in the hydro-sedimentological model correspond to the 2-year return period event and, therefore, represent more frequent flood scenarios. In general, for a 2-year return period event, the flow velocities within the channel system were low, with values around 1.5 m s^{-1} in the main channel, reaching up to 2.5 m s^{-1} in isolated locations. In the secondary channels, maximum velocities ranged between 0.5 and 1.0 m s^{-1}, due to the gentle slopes. Likewise, since the simulated event represents a high-frequency occurrence and the channels were designed for the PMP event, the maximum flow depths observed in the simulation were low compared to the channel dimensions. The greatest depths, ranging from 0.80 to 1.00 m, were observed in the main channel of the Chico Basin, where 25 to 30% of the channel cross-section was obstructed by sediment deposits.

Figure 7 presents the map of maximum sediment deposition along the drainage channels.

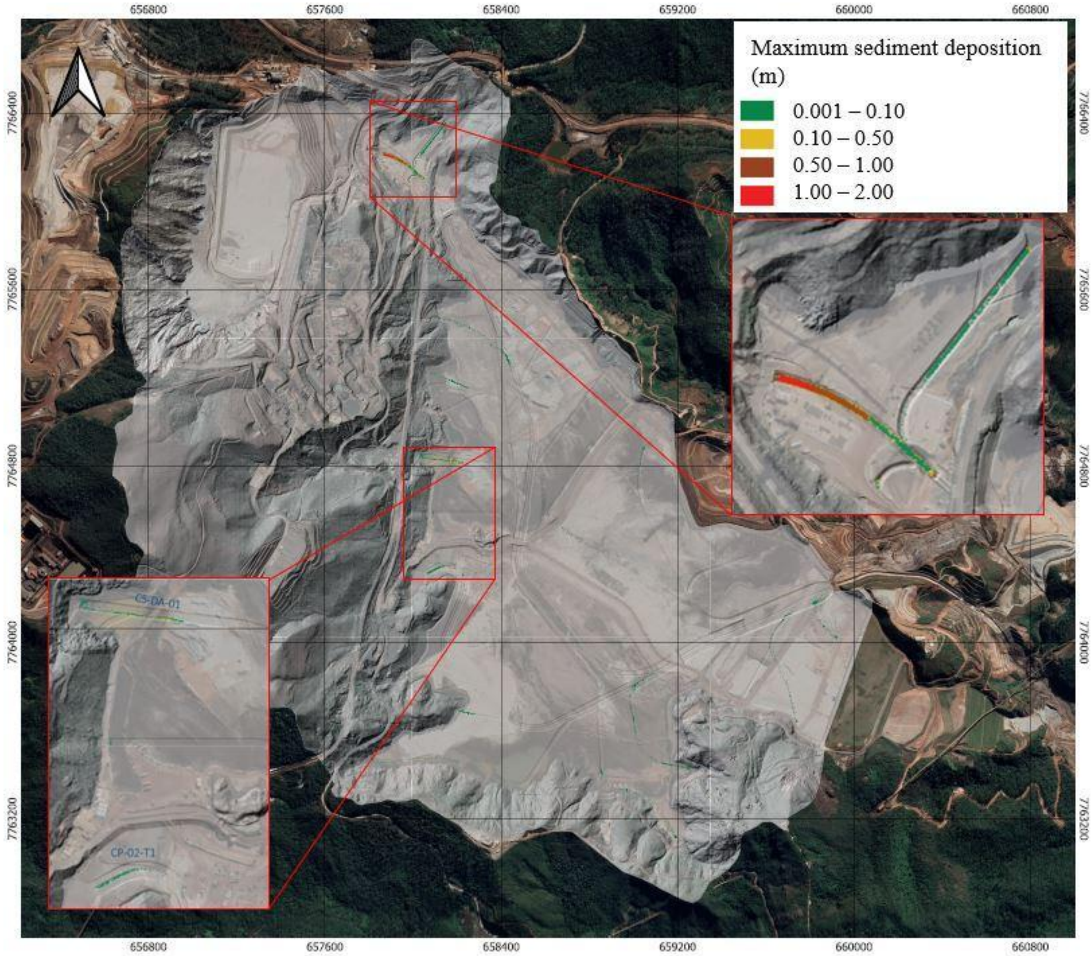

Figure 7. Maximum sediment deposition along the drainage system.

Overall, the 2-year return period rainfall event contributed minimally to sediment generation in the less anthropized sub-basins (located in the west and south) and in the reservoir embankment, which is characterized by very low slopes. As a result, only limited sediment deposition was observed in the channels receiving flow from these areas.

Conversely, the Chico Basin channels exhibited a marked tendency for sediment accumulation, primarily due to their low longitudinal slopes and the greater sediment load currently received from the Germano Pit Basin.

Field observations corroborate the model's results, revealing substantial sediment deposition in the Chico Basin channels, particularly in the main channel, which receives the largest contribution from the Germano Pit.

Additionally, the upstream channel segments – though to a lesser extent – also tended to accumulate sediment. According to the model, maximum deposition in these areas ranged from 1.00 to 2.00 m. This pattern results from flow originating in steeper areas encountering wide, low-slope channels, which reduces velocity and promotes particle settling.

4. CONCLUSIONS

The calibrated MUSLE, adjusted with sediment transport data from drone-based surveys of the Germano Pit wall, enabled more realistic estimates of sediment generation in the study area. Sediment transport modeling within the Germano Dam reservoir and Chico Basin drainage channels provided valuable insights into the spatial patterns of sediment accumulation under the occurrence of a recurring flood event. It should be noted, however, that the results are qualitative in nature. For more frequent rainfall events, the model indicated a generally low tendency for sediment accumulation across the channel system. The Chico Basin, which receives the entirety of the surface runoff from the Germano Pit, exhibited the greatest potential for sediment buildup.

Finally, this study highlights the potential of integrating empirical and numerical models calibrated with geotechnologies, to assess sedimentation risks in hydraulic structures located in mining areas.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. REFERENCES

ANAC (Brasil). **Regulamento Brasileiro da Aviação Civil: RBAC-E nº 94, Emenda nº 03: requisitos gerais para aeronaves não tripuladas de uso civil**. Date of issue: 3 Apr 2023. Avaliable at: https://www.anac.gov.br/assuntos/legislacao/legislacao-1/rbha-e-rbac/rbac/rbac-e-94. Access: 22 Dec. 2025.

BRASIL. Departamento de Controle do Espaço Aéreo. **ICA 100-40: aeronaves não tripuladas e o acesso ao espaço aéreo brasileiro**. 2023. Avaiable at: https://www.decea.mil.br/drone/docs/ICA%20100-40%20-%20Aeronaves%20n%C3%A3o%20Tripuladas%20e%20o%20Acesso%20ao%20Espa%C3%A7o%20A%C3%A9reo%20Brasileiro%202023%20-%20BCA%20103%2006.06.23.pdf. Access: 22 Dec. 2025.

BRASIL. Exército. Departamento de Ciência e Tecnologia. Norma da Especificação Técnica para Aquisição de Dados Geoespaciais Vetoriais de Defesa da Força Terrestre (ET-ADGV-Defesa F Ter): 1ª parte. 2. ed. Versão 1.1 (mar. 2016). (EB80-N-72.003). **Boletim do Exército**, n. 18, 6 maio 2016. Available: https://docs.ufpr.br/~deni_ern/CD2020/A1/ET_ADGV_2a_Edicao_2016_Textual_Anexo_A_Assinado.pdf. Access: 22 Dec. 2025.

BRITO, H.; FANTINATTI, G. F.; SILVA, R. M. N.; SILVA, R.; ROCHA JUNIOR, G. L. D.; GUERRA, Q. *et al.* Estimativa da produção de sedimentos da pilha de disposição de estéril CONVAP. **Revista Geociências**, v. 41, n. 1, p. 377-396, 2022. https://doi.org/10.5016/geociencias.v41i1.16446

CARVALHO, N. O. **Hidrossedimentologia prática**. Rio de Janeiro: Interciência, 2008. 599p.

GARCÍA, M. H. ASCE manual of practice 110 – Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. *In*: WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS, 21-25 May 2006, Omaha, Nebraska. **Proceedings[…]** ASCE Library, 2007. Article 94. https://doi.org/10.1061/40856(200)94

GOMES, L. L. **Avaliação espacial da perda de solo por erosão pela Equação Universal de Perda de Solo (EUPS) – Pilha de Estéril Sul – Carajás/PA.** 2012. 192f. Dissertação (Mestrado em Engenharia Geotécnica) – Universidade Federal de Ouro Preto, Escola de Minas, Núcleo de Geotecnia – NUGEO, Ouro Preto, 2012.

JIANG, C.; PARTELI, E. J. R.; SHAO, Y. A model for regional-scale water erosion and sediment transport and its application to the yellow river basin. **Journal of Advances in Modeling Earth Systems**, v. 17, n. 5, p. 1-27, 2025. https://doi.org/10.1029/2024MS004593

KINNELL, P. I. A.; RISSE, L. M. USLE-M: Empirical modeling rainfall erosion through runoff and sediment concentration. **Soil Science Society of America Journal**, v. 62, n. 6, p. 1667-1672, 1998. https://doi.org/10.2136/sssaj1998.03615995006200060026x

KURIQI, A.; KOÇILERI, G.; ARDIÇLIOĞLU, M. Recalling Meyer-Peter and Müller Approach for Assessment of Bed-Load Sediment Transport. **Preprints**, 2019. https://dx.doi.org/10.20944/preprints201904.0050.v3

MACHADO, M. L.; ALVES, J. S.; GOMES, I.; VIEIRA, E. M. SIMÃO, M. L. R.; NAIME, U. J. Levantamento sistemático dos fatores da Equação Universal de Perdas de Solos (USLE) para o delineamento de áreas com potencial erosivo da bacia PN1 – IGAM, Minas Gerais (resultados parciais). *In*: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 14., 25-30 Apr. 2009, Natal, **Proceedings[...]** São José dos Campos: INPE, 2009. p. 7733-7739.

MAGALHÃES, D. M. **Uso de drones como suporte ao planejamento territorial: da coleta de dados à geovisualização.** 2021. Tese (Doutorado em Geografia) - Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Geografia, Belo Horizonte, 2021.

MAGALHÃES, D. M.; MOURA, A. C. M. Análise da morfologia de modelos digitais de superfície gerados por VANT. **Revista Brasileira de Cartografia**, v. 73, n. 3, p. 707–722, 2021. https://doi.org/10.14393/rbcv73n3-51600

MANTOVANI, V. A.; AMORIM, J. S.; RODRIGUES, A. F.; JUNQUEIRA, R.; CARVALHO, R. N.; OLIVEIRA, A. S. Estimativas da taxa de entrega de sedimentos e áreas susceptíveis à erosão em uma bacia hidrográfica no sul de Minas gerais – Brasil. **Revista da Universidade Vale do Rio Verde**, v. 16, n. 2, p. 1-10, 2018. http://dx.doi.org/10.5892/ruvrd.v16i2.5061

MEYER-PETER, E.; MULLER, R. Formulas for bed-load transport. *In*: MEETING OF THE INTERNATIONAL ASSOCIATION FOR HYDRAULIC STRUCTURES RESEARCH, 2., 1948, Stockholm. **Proceedings[…]** IAHSR, 1948. p. 39–64.

NUNES, E. D.; ROMÃO, P. A.; SALES, M. M.; SOUZA, N. M.; LUZ, M. P.; RIBEIROS, L. F. Variabilidade espacial da geração e conectividade de sedimentos em bacias de UHES. **Mercator**, v. 21, e21026, p. 1-15, 2022. https://doi.org/10.4215/rm2022.e21026

SANTOS, A. P.; MEDEIROS, N. G.; SANTOS, G. R.; RODRIGUES, D. D. Avaliação da acurácia posicional planimétrica em modelos digitais de superfície com o uso de feições lineares. **Boletim de Ciências Geodésicas**, v. 22, p. 157-174, 2016. http://dx.doi.org/10.1590/s1982-21702016000100009

SIDIROPOULOS, E.; VANTAS, K.; HRISSANTHOU, V.; PAPALASKARIS, T. Extending the Applicability of the Meyer–Peter and Müller Bed Load Transport Formula. **Water**, v. 13, 2817, p. 1-18, 2021. https://doi.org/10.3390/w13202817

SILVA, G. R.; FAGUNDES, H. O.; FASSONI-ANDRADE, A. C. Estudo comparativo da concentração de sedimentos em suspensão utilizando medições *in situ*, modelagem hidrossedimentológica e estimativas por satélite. In: SIMPÓSIO NACIONAL DE MECÂNICA DOS FLUIDOS E HIDRÁULICA, 2., 26-30 Aug. 2024, Curitiba. **Proceedings[...]** ABRHidro, 2024. p. 1-8.

USEPA. **Erosion and Sediment Control**: Surface Mining in the Eastern U.S. Volume I. Planning. Volume II. Design. EPA/625/3- 76/006a. Washington, D.C., 1976.

WATT, W. E.; CHOW, K. C. A. A general expression for basin lag time. **Canadian Journal of Civil Engineering**, v. 12, n. 2, p. 294-300, 1985. https://doi.org/10.1139/l85-031

WILLIANS, J. R. Sediment-yield prediction with universal equation using runoff energy factor. *In*: PRESENT AND PROSPECTIVE TECHNOLOGY FOR PREDICTING SEDIMENT YIELD AND SOURCES, 28-30 Nov. 1972, Oxford, Mississippi. **Proceedings[…]** Washington, DC: U.S. Department of Agriculture, Agricultural Research Service, 1975. (ARS-S-40). p. 244-252.