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ENVIRONMENTAL PERFORMANCE OF A MICRO-BASIN AND ITS HYDROSSEDIMENTOLOGICAL RELATIONSHIP WITH THE NDVI VEGETATION INDEX

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ABSTRACT

Objective: The environmental performance in controlling sediment production was evaluated in a microcatchment in Iguatemi (MS), relating sediment production to the NDVI vegetation index between 2022 and 2024.

Theoretical Framework: Quantifying suspended sediments is essential in hydrosedimentological and erosion studies in watersheds. The environmental performance index proposed by D'Agostini, Denardin, & Lemainski (2017) calculates the environment's capacity to dissipate the rainfall erosivity, and the results indirectly reflect human action through different proportions of land use and cover, and the types of management applied to them.

Method: An automated system with level, turbidity, and rain gauges estimated the concentration of suspended solids during 59 erosive rainfall events.

Results and Discussion: Throughout monitoring time, the micro-basin exported about 21.6 Mg of sediments, influenced mainly by areas without vegetation cover and by livestock trampling. The erosivity dissipation index (IDE) varied between 0.64 and 0.99, following the NDVI, except in periods without the presence of cattle, when the IDE remained high even with less vegetation cover.

Research Implications: Highlighting the importance of conservation practices, vegetation recovery, and cattle exclusion in the headwater area to reduce sediment load and improve the micro-basin's environmental performance.

Originality/Value: Contributing to the literature by studying the environmental performance of managing an area with a predominance of sandy soils and in the process of environment recovery.

Keywords: Sediment, Watershed, Sandy Soil, Erosion.

DESEMPENHO AMBIENTAL DE UMA MICROBACIA E SUA RELAÇÃO HIDROSSEDIMENTOLÓGICA COM O ÍNDICE DE VEGETAÇÃO NDVI

RESUMO

Objetivo: Avaliou-se, entre 2022 e 2024, o desempenho ambiental no controle de produção de sedimentos de uma microbacia em Iguatemi (MS) relacionando a produção de sedimentos ao índice de vegetação NDVI.

Referencial Teórico: Quantificar sedimentos em suspensão é essencial em estudos hidrossedimentológicos e de erosão em bacias hidrográficas. O índice de desempenho ambiental proposto por D'Agostini, Denardin, & Lemainski (2017) calcula a capacidade do ambiente em dissipar a erosividade da chuva e os resultados refletem

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indiretamente a ação do homem sobre as terras, por meio das diferentes proporções de uso e cobertura do solo e tipos de manejos aplicados nelas.

Método: Um sistema automatizado com sensores de nível, turbidez e pluviômetro estimou a concentração de sólidos em suspensão durante 59 eventos erosivos de chuva.

Resultados e Discussão: A microbacia exportou cerca de 21,6 Mg de sedimentos, influenciados principalmente por áreas sem cobertura vegetal e pelo pisoteio do gado. O índice de dissipação de erosividade (IDE) variou entre 0,64 e 0,99, acompanhando o NDVI, salvo em períodos sem presença de gado, quando o IDE se manteve elevado mesmo com menor cobertura vegetal.

Implicações da Pesquisa: Destacar a importância de práticas conservacionistas, recuperação da vegetação e exclusão do gado na área da nascente para reduzir a carga de sedimentos e melhorar o desempenho ambiental da microbacia.

Originalidade/Valor: Contribuir para a literatura ao estudar o desempenho ambiental do manejo de uma área com predominância de solos arenosos e em processo de recuperação.

Palavras-chave: Sedimento, Bacia Hidrográfica, Solo Arenoso, Erosão.

DESEMPEÑO AMBIENTAL DE UNA MICROCUENCA Y SU RELACIÓN HIDROSEDIMENTOLÓGICA CON EL ÍNDICE DE VEGETACIÓN NDVI

RESUMEN

Objetivo: Se evaluó el desempeño ambiental en el control de la producción de sedimentos en una microcuenca en Iguatemi (MS), relacionando la producción de sedimentos con el índice de vegetación NDVI entre 2022 y 2024

Marco Teórico: Cuantificar sedimentos en suspensión es esencial en estudios hidrosedimentológicos y de erosión en cuencas hidrográficas. El índice de desempeño ambiental propuesto por D'Agostini, Denardin, & Lemainski (2017) calcula la capacidad del ambiente para disipar la erosividad de la lluvia, y los resultados reflejan indirectamente la acción del hombre sobre la tierra, a través de las diferentes proporciones de uso y cobertura del suelo y los tipos de manejo aplicados en ellas.

Método: Un sistema automatizado con sensores de nivel, turbidez y un pluviómetro estimó la concentración de sólidos en suspensión durante 59 eventos erosivos de lluvia.

Resultados y Discusión: Durante el período, la microcuenca exportó cerca de 21.6 Mg de sedimentos, influenciados principalmente por áreas sin cobertura vegetal y por el pisoteo del ganado. El índice de disipación de la erosividad (IDE) varió entre 0.64 y 0.99, siguiendo al NDVI, salvo en períodos sin presencia de ganado, cuando el IDE se mantuvo elevado incluso con menor cobertura vegetal.

Implicaciones de la investigación: Destacar la importancia de prácticas conservacionistas, recuperación de la vegetación y exclusión del ganado en el área del nacimiento del río para reducir la carga de sedimentos y mejorar el desempeño ambiental de la microcuenca.

Originalidad/Valor: Contribuir a la literatura al estudiar el desempeño ambiental del manejo de un área con predominancia de suelos arenosos y en proceso de recuperación.

Palabras clave: Sedimento, Microcuenca, Suelo Arenoso, Erosión.

1 INTRODUCTION

Watersheds are areas spatially delimited by watershed divides, consisting of an interconnected drainage network, whose runoff converges into a common section, called the mouth or outlet (Mello and Silva, 2013). It is considered a physical, open, and dynamic system.

According to Carvalho (2008), sediment is defined as a particle derived from rock or biological material, capable of being transported by water or wind. Transportation can occur from the place of origin or from some point in the landscape, and sediment can be deposited temporarily or even permanently; its study is crucial for addressing issues such as soil loss, water quality and quantity, as well as its ecological and recreational impacts (Horowitz, 2008).

The dynamics of sediment are complex, as they are determined by gravitational force and kinetic energy. These forces are generated by the impact of raindrops and surface runoff, leading to the detachment, transport, and deposition of sediment (Pellegrini, 2013; D'Agostini *et al*., 2017) and are directly related to water erosion and sediment production in a micro-watershed. This dynamic is influenced and altered by anthropogenic activities due to changes in land use and management (Bruijnzeel, 2004). Erosion is the anthropogenic factor that most negatively affects watersheds (Valentino, 2019).

Changes to the basin's surface have significant impacts on runoff. This impact is typically characterized by its effect on flood patterns, minimum flows, and mean flow (Tucci & Clarke, 1997).

Among the variables used to assess land-use change, vegetation indices have been the most widely used (Guilherme *et al*., 2016). Through such indices, it becomes possible to characterize and quantify biophysical parameters of forests, agricultural crops, and changes in land use, as they reduce the complexity of the multispectral information provided by satellites (Tucker, 1979) and, according to Guilherme *et al.* (2016), the Normalized *Difference* Vegetation Index (NDVI) is cited by many authors as one of the most widely accepted indices for analyzing vegetation cover using remote sensing (Holben *et al*., 1980), and authors such as Melo *et al.* (2011), Lima *et al*. (2013), Silva *et al*. (2013), Carvalho *et al*. (2014), and Sousa *et al*. (2016) sought to establish the use of this index in estimating and explaining water erosion. The presence of vegetation cover drastically reduces the impact of raindrops on the soil surface, thereby reducing the detachment of surface particles (Coelho Netto, 2021)

The term "sediment yield" refers to the amount of sediment exported from the watershed or a given area, but it is only a fraction of the total erosion occurring in the watershed, as there are temporary or permanent deposits that mitigate soil losses from that location. Surface water runoff is the primary agent for transporting soil particles (sediment) (Pruski *et al*., 2003). Once incorporated into the watercourse, eroded sediments are called hydrosediments, which can be transported by suspension or bedload. When there is insufficient transport energy, they are deposited at the bottom of the water body, resulting in sedimentation (Mello Neto *et al*., 2017).

Several factors determine sediment production, notably: the intensity of rainfall and surface runoff, the basin's topography, the texture, size, and stability of soil aggregates, the degree of consolidation and the roughness of the soil surface, the presence of erosion, and soil cover by crop residues (Hudson, 2015).

Continuously quantifying suspended sediments in watersheds is fundamental, as it reflects the erosion rates caused by the energy of rainfall and surface runoff on different land-use proportions, land cover, and management practices (Minella *et al*., 2008; Manso *et al*., 2022), and monitoring at the outlet is essential. This continuous monitoring can be done directly—which requires high costs in human resources or even in the acquisition of efficient automatic samplers—or indirectly—using turbidimetry (Pellegrini, 2013). This type of monitoring can be important in payments for environmental services (PES) initiatives and their implementation by producers and rural extension agents (Chaves, 2010)

Recent studies have focused on the development of indirect methods and automated systems to measure erosion. Portocarrero (2017) implemented an automated sediment monitoring system aimed at the revegetation of degraded areas. Pellegrini (2013) applied automated monitoring to determine the environmental performance index in two paired sub-basins with different land uses and land covers. Bartels (2015) employed instrumentation to monitor precipitation and sediment production over six months, evaluating different conditions of land use and management.

Among the authors cited here, Portocarrero (2017) emphasized that such methods and systems tend to fill a major gap, as they make it possible to align data collection intervals with other automated field measurements, such as soil water monitoring and agrometeorological parameters, where significant technological advancements have been made . The assessment of runoff turbidity, despite being an indirect method for determining the concentration of suspended sediments, has been used successfully (Bradley, 1956; Didoné, 2013; Chagas, 2015; and Tiecher *et al*., 2017).

The method is called nephelometric (Pellegrini, 2013), and in this method, a beam of light incident on the sample has part of its rays refracted by the suspended particles, while the remainder of the beam passes through the solution. However, the validation of the results depends on the sensor calibration process. According to Pinheiro *et al*. (2013) and Sari *et al*.

(2012, 2015, 2017), the concentration of suspended sediments, as estimated by the turbidimeter when calibrated in the laboratory using a composite sample of basin soil, is reliable up to a certain turbidity range.

Finally, according to Pellegrini (2013), the quantification of suspended sediments is essential for monitoring and hydrosedimentological studies in watersheds, and highlights that the results indirectly reflect human impact on the land through different proportions of land use and cover and the types of management practices applied to them, thereby establishing the environmental performance index as proposed by D'Agostini *et al*. (2017). In this index, the closer the values are to unity, the greater the environment's capacity to dissipate erosivity.

2 METHODOLOGY

The headwaters area used in this study is located in the municipality of Iguatemi, in the southwest of the state of Mato Grosso do Sul. (Figure 1)

Figure 1

Geographic location of the study area

Source: Adapted from Wikipedia (2024)

The local geographic coordinates, in decimal degrees, are: latitude -23.620887° S, longitude -54.564593° W, and elevation of 344 m a.s.l. The average slope is 4.2%, and the predominant soil type is a quartz-sandy arenosol with a sandy texture. The region's climate, according to the Köppen system, is of the Cfa type—humid subtropical, mesothermal, with mild winters and hot summers, significant precipitation in all months of the year, an average temperature in the coldest month > 10°C, and an average temperature in the hottest month > 22°C. (Aparecido *et al*., 2020)

A flow measurement structure in the form of a rectangular weir (Figure 2b) was installed in November 2022 at the headwaters of the drainage system that flows into the Panduí stream, a tributary of the Iguatemi River, which in turn flows into the right bank of the Paraná River.

An automatic monitoring system from *Campbell Scientific* was added to this setup, consisting of a CR1000 data logger, which collected and stored data every 5 minutes, and sensors connected to it: a CS475L water level sensor, an OBS3+ turbidity sensor, a CS474 electrical conductivity and water temperature sensor, a CS650 soil water content, temperature, and electrical conductivity sensor, as well as a TB4 high-intensity rain gauge (Hydrological Service). (Figure 2b).

Figure 2

Monitoring setup. (a) Data logger and (b) spillway.


(a) (b)

The concentration of suspended solids (sediments) was estimated based on readings from the turbidity sensor, calibrated with soil collected in the microbasin's catchment area, according to Gonçalves (2019).

The following tasks were performed every two weeks: cleaning the sensors in the water; cleaning the channel, removing silt and invasive vegetation; checking the rain gauge; and maintaining and cleaning the photovoltaic system.

The collected and processed data were used to establish the environmental performance index for the management of the micro-basin's catchment area (spring), or Erosivity Dissipation Index (EDI), according to the methodology proposed by D'Agostini *et al.* (2017), based on the selection of events considered erosive as defined by ~~(~~Carvalho *et al.*~~,~~ 2004) during the period from November 2022 to June 2024.

NDVI data from the MODIS time series were obtained using the Vegetation Temporal Analysis System (SATVeg) algorithm (Embrapa Digital Agriculture, 2025) and subsequently filtered using the Savitzky-Golay method (Savitzky & Golay, 1964).

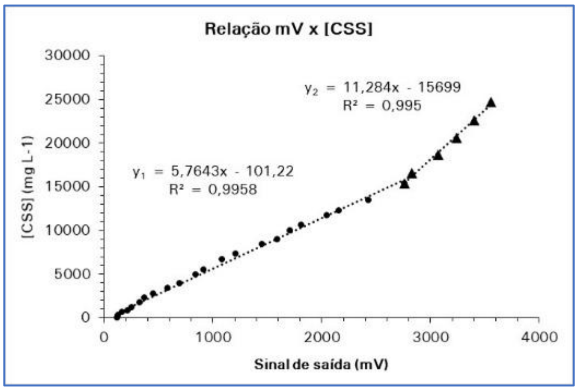
The algorithm calculated an average pattern based on the delineation ~~of~~ the study ~~microbasins,~~ resulting in a time series that served as supporting data for interpreting the results obtained from the IDE index calculation.

3 RESULTS AND DISCUSSION

The concentration of suspended solids ([CSS]—sediments) was determined indirectly (Figure 3) using readings from the OBS3+ turbidity sensor, calibrated with soil collected in the microbasin's catchment area, as described by Gonçalves (2019).

Figure 3

Correlation curve between turbidity readings and suspended solids concentration [SSC]. In y_1*for values below 2800 mV and* y_2*for values above 2800 mV.*



Thus, the electrical output signal in millivolts was converted to ~~[~~SSC~~]~~ according to equations 1 and 2. When multiplied by the flow rate (L $^{s^{-1}}$) and the duration, an estimate of the total sediment transported during a given rainfall event was obtained.

$[CSS]_1$ (mg $^{L^{-1}}$) = 5.7643* mV – 101.22 (1)

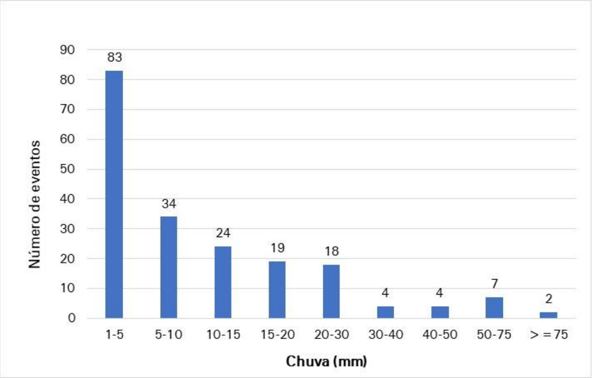
$[CSS]_2$ (mg $^{L^{-1}}$) = 11.284 * mV - 15699.952 (2)

Where mV is the sensor output voltage in millivolts and [CSS] is the concentration of suspended solids.

Rain events were separated as proposed by D'Agostini *et al*. (2017) using algorithms embedded in the spreadsheet that stored the data. A total of 2,200 mm of rainfall and 78 rain events considered erosive were recorded (Figure 4).

Figure 4

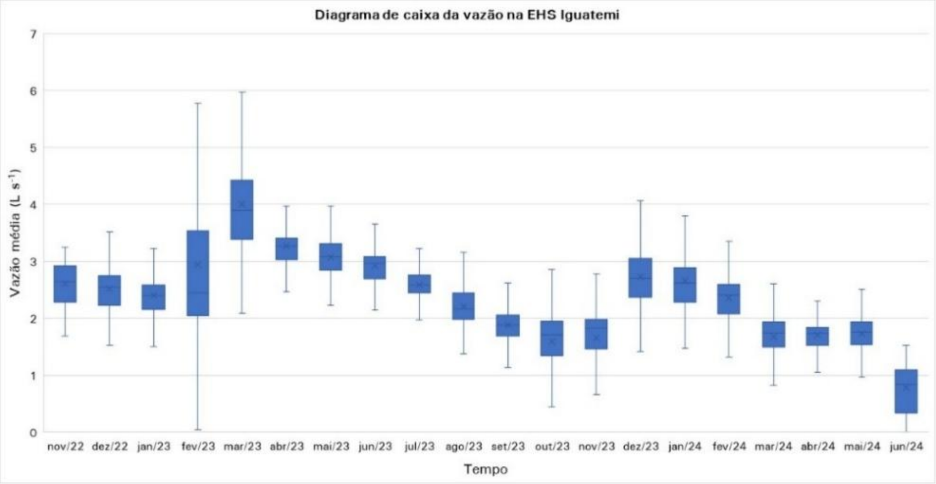
Histogram of rainfall events in the study area.



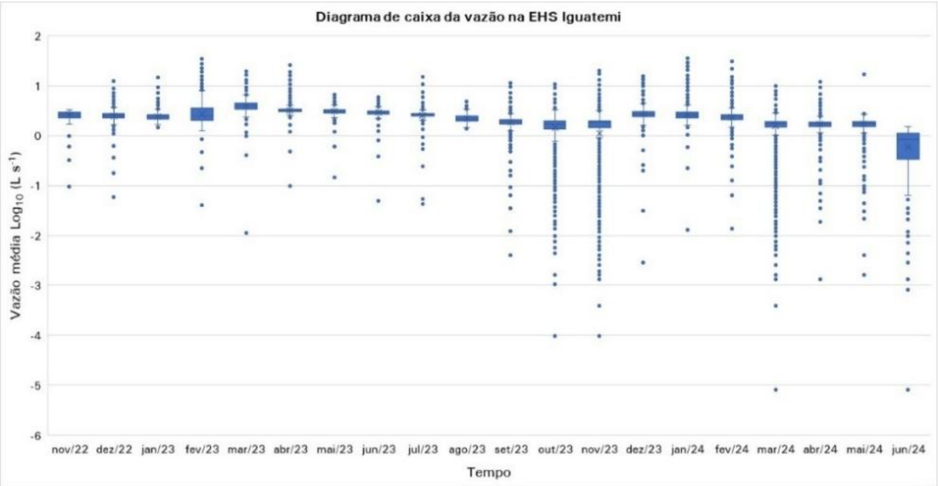
The maximum 1-hour rainfall (44.4 mm), the maximum hourly intensity based on 5-minute data (140.1 mm $^{h^{-1}}$), and the maximum daily rainfall (82 mm) occurred in February 2023. The average flow rate was 2.50 l $^{s^{-1}}$, or 9 m^3 $^{h^{-1}}$. The periods of highest flow were recorded during the summer (Figure 5), and during the monitoring period, the region experienced a severe drought, reaching the point of drying up and recording zero flow. (Figure 6)

Figure 5

Box plot of water flow at the monitored spring. In (a) the average flow and in (b) the average flow on a $\log_{10}$scale for better visualization of outliers.



(a)



(b)

Figure 6

View of the study area in July 2024. In (a) the downstream situation and (b) the upstream situation.

(a) (b)

It is estimated that 21.6 Mg of soil was carried into the watercourse during the erosive events. Field investigations showed that much of this material may have originated from a portion of the land that was without vegetation cover (Figure7 a) as well as from cattle movement in the upstream area (Figure7 b).

Figure 7

View of the monitored area on two occasions. Portions of the land without vegetation in November 2022 and with the newly constructed terraces (a) and in January 2024 without vegetation and with the presence of cattle (b). The measurement point is highlighted.

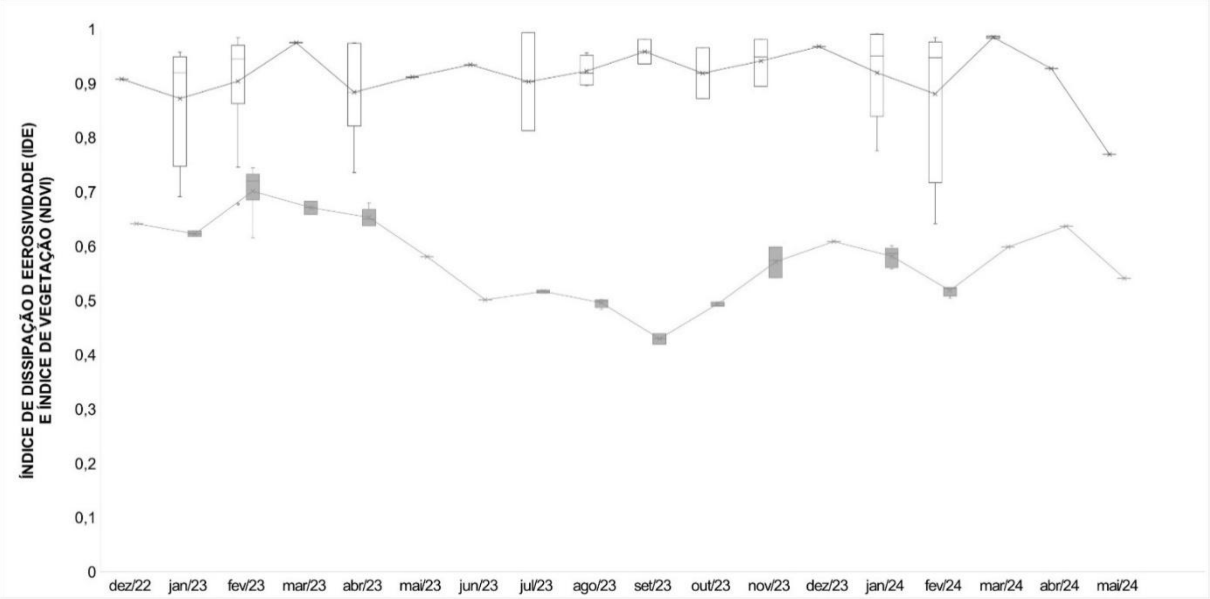
(a) (b)

Source: Adapted from Google (2024).

The IDE tracked changes in the NDVI (Figure 8). An important point to note is that from June to October 2023, the indices showed an inverse relationship; that is, while the NDVI decreased, the other remained above 0.9. This can be explained by the fact that it was a period of property ownership transition, during which cattle did not have access to the area. An interesting finding was that, consistent with the January 2024 image (Figure 7b), the presence of cattle in the area combined with the low vegetation index resulted in the lowest IDE values recorded.

Figure 8

Variation in the Erosivity Dissipation Index (IDE) and vegetation condition (NDVI) (dark boxes) between November 2022 and June 2024.



According to Bertol & Almeida (2000), when studying a basin with a predominance of Nitossolo, soil loss was 12 Mg $^{\mathrm{ha^{-1}year^{-1}}}$. Oliveira *et al*. (2015), however, found 19.65 Mg $^{\mathrm{ha^{-1}}}$over 15 months in an area with the same soil type and warn that these figures underscore the need for caution in the construction and maintenance of road networks, as roads were the primary cause of flash floods when compared to the other land uses studied. Hernani *et al*. (1999), when studying a dystrophic Red Latosol with a slope of 3.9% in the state of Mato Grosso do Sul, found values of 6.9 Mg $^{\mathrm{ha^{-1}year^{-1}}}$. Alves *et al.* (2021), on the other hand, found values of 49 Mg $^{\mathrm{year^{-1}}}$in an area of the state of São Paulo with a slope greater than 12% and a predominance of Quartzarenic Neosols. Moura-Bueno *et al*. (2018), when studying cropland areas where Neossols predominated, found values ranging from 13.36 to 79.71 Mg $^{\mathrm{ha^{-1}year^{-1}}}$.

In this context, the adoption of soil and water conservation practices, such as those proposed by Casarin and Oliveira (2018), could be of great value, since the effects of vegetation restoration and the protection of springs against livestock access have been masked. This understanding is corroborated by Calheiros *et al.* (2009), where the entire watershed area warrants attention regarding soil preservation, and all conservation techniques—aimed at both combating erosion and improving soil physical characteristics, notably those related to the infiltration capacity of rainwater or irrigation water—will result in greater d water availability at the spring in terms of quantity and stability throughout the year, including during the dry season.

The maintenance, or even the establishment of permanent protection areas (PPAs) and the protection of springs against livestock entry, is a fundamental measure for reducing sediment load in watercourses, as evidenced by several studies in the field (Pinto *et al.*, 2012; Agrizzi *et al.*, 2018; Oliveira *et al.*, 2020). Cattle trampling compacts the soil, reducing its capacity to infiltrate rainwater. Consequently, surface runoff increases, carrying soil particles into rivers, streams, lakes, and reservoirs. This erosive dynamic is intensified by the removal of vegetation along the banks of springs and other surface water sources, as this vegetation effectively acts as a natural barrier against erosion.

As observed in the monitored area (Figure 3b), Confessor *et al.* (2022) report that the creation of trails by livestock also contributes to the direction of water flow, intensifying erosion and sediment transport. The high sediment load in watercourses has several negative impacts, such as: sediment deposition in rivers and reservoirs reduces their storage capacity and increases the risk of flooding; degradation of water quality, as pollutants such as pesticides and fertilizers may be transported simultaneously, contaminating the water and harming aquatic life.

During the period when no cattle were observed entering the spring area, several positive effects were noted, such as improved erosion control, since vegetation protects the soil, reducing the impact of raindrops and preventing the detachment of particles.

Other important measures that could be adopted to protect the monitored spring include vegetation restoration through the planting of native species, including trees. Leal *et al*. (2017) note that when vegetation restoration in permanent preservation areas is not effectively carried out with native species, negative changes in the hydrological cycle and natural regeneration in the understory may occur.

On the other hand, the installation and maintenance of fences to prevent animals from entering preservation areas, as well as the adoption of appropriate management systems in agriculture and livestock farming, effectively reduce the impact of human activities on the environment. These effects were observed during the first months of monitoring in this study (June to September 2023), when, despite a reduction in the NDVI vegetation index, environmental performance in sediment control remained high. (Figure 5)

4 CONCLUSION

The environmental performance index for sediment production control (IDE) ranged from 0.64 to 0.99, with a mean of 0.89 and a standard deviation of 0.12. The NDVI followed the variation in the IDE, demonstrating the importance of vegetation cover in the system and in protecting the spring.

Sediment production in the area of influence of the hydrosedimentological station is estimated at 21.6 Mg. The adoption of soil and water conservation practices, such as revegetation efforts in the permanent preservation area of the spring and along the watercourse, proper maintenance of terraces and pasture quality around the spring, as well as effectively preventing livestock from entering the APP, constitutes a fundamental measure to reduce the sediment load in the water source.

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