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DIRECT AND INDIRECT ASSESSMENTS OF SOIL ERODIBILITY IN THE TUCURUÍ HYDROELECTRIC POWER PLANT RESERVOIR

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Abstract

The Tucuruí Hydroelectric Power Plant (HPP), is the 5th largest hydroelectric dam in the world in generating capacity and it transfers electric power to several Brazilian states. Because of its reservoir of 2,917 km², it is strongly subject to the manifestation of erosive processes. Several studies report the occurrence of erosive features near its lake, besides being constantly subject to lamin’’ar erosive actions in its drainage areas. In this work, direct and indirect assessments of samples of erodibility from the main soils in the Tucuruí HPP reservoir were performed. The indirect ones employed formulations based on physical characteristics of the soil and the direct ones tested undisturbed samples under runoff, gradual and total water immersion processes, and under intense levels of compaction, for evaluations in the Miniature, Compacted, Tropical (MCT) methodology. It was verified that the samples classified as Argisol and Yellow Oxisol presented medium erodibility rates and low levels of disaggregation, while the Red Oxisol presented low erodibility level, medium to high levels of disaggregation, and expansions in the MCT. These conclusions indicate that the agricultural activity in the area must favor crops that maintain the surface coverage on the first two soils mentioned and avoid uses that may disrupt and cause compaction on the last one.

Keywords: Erodibility; Tucuruí HPP; Inderbitzen

AVALIAÇÕES DIRETAS E INDIRETAS DA ERODIBILIDADE DE SOLOS DO RESERVATÓRIO DA USINA HIDRELÉTRICA DE TUCURUÍ

Resumo

A UHE Tucuruí, além de ser a 5º maior hidrelétrica do mundo em capacidade de geração, promove energia a vários estados brasileiros, e, tendo um reservatório de 2.917 km², está fortemente sujeita à manifestação de processos erosivos. Diversos trabalhos relatam a ocorrência de feições erosivas nas proximidades de seu lago, além de estar constantemente sujeita a ações erosivas laminares em suas áreas de drenagem. Neste trabalho foram realizados análises diretas e indiretas da erodibilidade de amostras dos principais solos do reservatório da UHE Tucuruí. As análises indiretas empregaram formulações baseadas em caraterísticas físicas dos solos e as diretas testaram amostras indeformadas sob escoamento superficial, processos de imersão gradual e total em água, e sob intensos níveis de amolgamento, para avaliações na metodologia Miniatura Compactada Tropical – M.C.T. Verificou-se que as amostras classificadas pedologicamente como Argissolo e Latossolo Amarelo apresentaram médias taxas de erodibilidade e baixos níveis de desagregação, enquanto o Latossolo Vermelho apresentou baixa erodibilidade, médios a altos níveis de desagregação, e expansões na metodologia M.C.T.. Tais conclusões indicam que a atividade agrícola da área deve privilegiar culturas que mantenham a cobertura superficial das áreas dos primeiros solos e a prevenção de usos que possam desestruturar e amolgar o último solo..

Palavras-chave: Erodibilidade; UHE-Tucuruí; Inderbitzen.

AVALIAÇÕES DIRETAS E INDIRETAS DA ERODIBILIDADE DE SOLOS DO RESERVATÓRIO DA USINA HIDRELÉTRICA DE TUCURUÍ

Resumen

La UHE Tucuruí, además de ser la quinta central hidroeléctrica más grande del mundo en términos de capacidad de generación, abastece de energía a varios estados brasileños y, con un embalse de 2.917 km², está fuertemente sujeta a la manifestación de procesos erosivos. Varias obras reportan la ocurrencia de rasgos erosivos en las cercanías de su lago, además de estar constantemente sometidas a acciones erosivas laminares en sus áreas de drenaje. En este trabajo se realizaron análisis directos e indirectos de la erosionabilidad de muestras de los principales suelos del embalse UHE Tucuruí. Los análisis indirectos utilizaron formulaciones basadas en características físicas de los suelos y los directos probaron muestras no perturbadas bajo escorrentía superficial, procesos de inmersión gradual y total en agua y bajo niveles intensos de abolladuras, para evaluaciones en el Tropical Compactado Miniatura - M.C.T. Se encontró que las muestras clasificadas pedológicamente como Ultisol y Latosol Amarillo presentaron índices de erosionabilidad medios y niveles bajos de desagregación, mientras que Latosol Rojo presentó niveles de erosionabilidad bajos, niveles de desagregación medios a altos y expansiones en la metodología MCT. Actividad agrícola en el área debe favorecer cultivos que mantengan la cobertura superficial de las áreas de los primeros suelos y la prevención de usos que puedan desestructurar y abollar el último suelo.

Palabras-clave: Erodibilidad; UHE-Tucuruí; Inderbitzen.

1. INTRODUCTION

The Tucuruí Hydroelectric Power Plant, installed in the municipality of Tucuruí, in the State of Pará, northern region of Brazil has a generation capacity of 8,375 MW. It is currently the fifth largest hydroelectric plant in the world, providing energy to nine Brazilian states, with more than 30 years old, and inserted in the Amazon biome. It is considered, according to the World Commission on Dams - WCD (2000), as a landmark for Brazil and the world, having one of the largest water reservoirs ever built and in its maximum quota, with an extension of 175 km, a volume of 50,3 billion m³ and an area of 2917 km².

According to the WCD (2000), the Tocantins hydrographic basin is in the geological province of the Eastern Amazon, characterized by distinct geological environments, depending on the time in which they originated and the two tectonic events to which they were subjected. In particular, the area of influence of the Tucuruí reservoir is characterized by two geological domains, one being the crystalline basement, comprising igneous and meta-sedimentary rocks, and the other by a sedimentary cover, comprising sediments that were deposited during the Mesozoic and Cenozoic (tertiary and quaternary). In this way, the reservoir is in the contact zone between the crystalline rocks of the Xingú Complex, on the left bank, and with low-grade metamorphic rocks of the Tocantins group, on both of its banks and its riverbed (CMB, 1999).

Also, according to the WCD (1999), the Tucuruí dam implementation site is at the end of a long stretch of river, which can be divided into three relief units, the Northern Plateau Pará-Maranhão, Lowered Plateau of the Amazonas, and the Peripheral Depression in the south of Pará, which almost completely covers the reservoir area, having its origin in erosive processes initiated at the end of the tertiary period, including several forms of relief in the region, such as areas with pediplain surfaces, dissected areas of flat-topped hills and river plains.

According to the Brazilian Institute of Geography and Statistics - IBGE (2002), cited by the Ministry of Regional Development - MDR (2018), the soils that form the hydroelectric reservoir are predominantly Red-Yellow Argisol – PVA, Yellow Oxisol – LA, and Red-Yellow Oxisol – LVA. In its bed, there are deposits of sedimentary materials (Figure 1) with the colors gray, light brown, dark brown, and white, respectively, being normally considered as acid, of low natural fertility and quantified in 60% Argisols, 25% Red-yellow and Yellow Oxisols, and 15% of other types, according to the World Commission on Dams - CMB (2000).

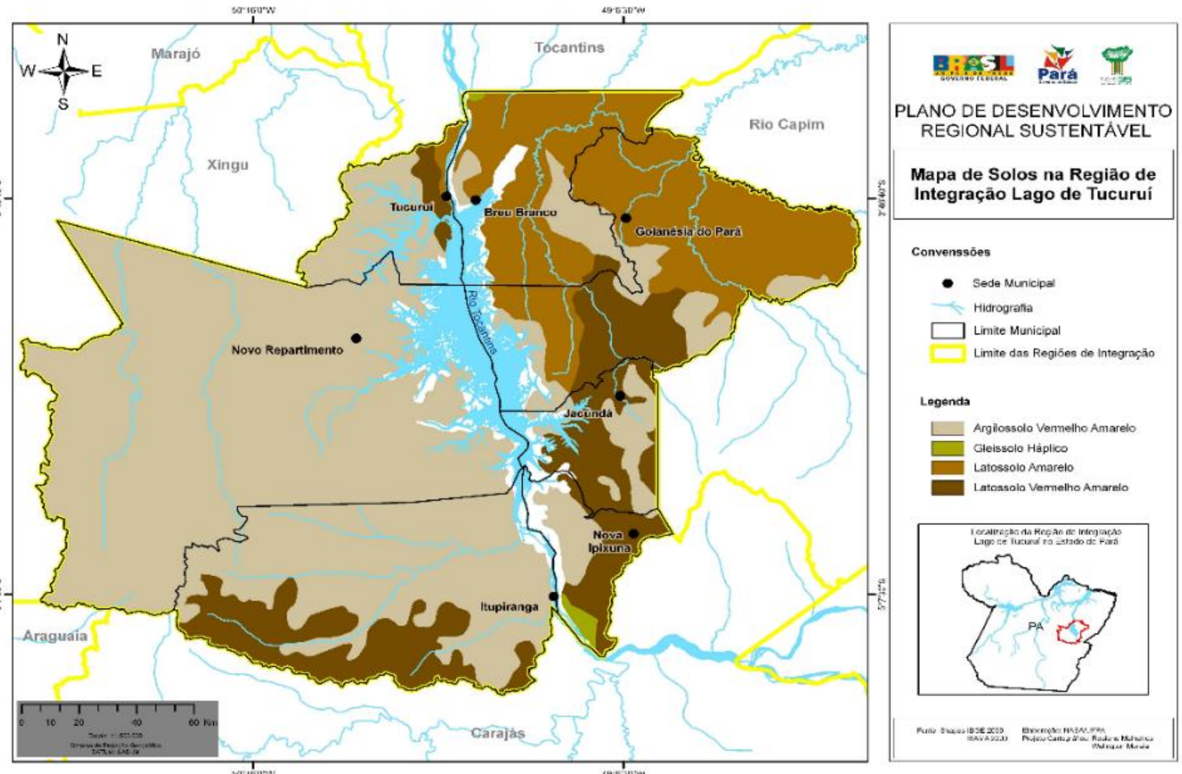


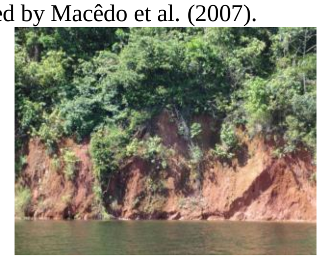
Figure 1 - Pedological soil map of the Tucuruí lake integration area. Source: Ministry of Regional Development - MRD (2018).

In hydroelectric projects, the risk of silting up reservoirs must be considered, regardless of their size. Thus, according to the National Electric Energy Agency – NEEA (2000), considering this risk, the Tucuruí HPP has a useful life of 1000 years. However, campaigns of hydrosedimentological studies on the tributaries of the Tocantins and Araguaia rivers, from 1975 to 1982, pointed out only 400 years of useful life as a guarantee for the safety of the power generation equipment (ELETRONORTE, 1988). The current scenario greatly differs from the previous ones, as they did not consider the increase of deforested areas (FEARNDISE et al., 2015).

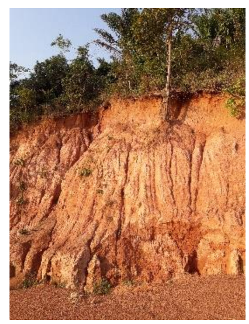
The transformation of the reservoir area was assessed at different spatial and temporal scales: from 1996 to 2001, presenting a slight reduction in its forest areas (VASCONCELOS and NOVO, 2004); on a larger time scale, from 1988 to 1999, observing deforestation rates of 70,673 ha/year (MONTOYA et al., 2018) analyzing only the area of the Municipality of Novo Repartimento, that holds 38,5% of the reservoir area (MRD, 2018). From 2000 to 2013, there was an increase of 141.67% in deforested areas (FARIAS et al., 2018). This way, it is possible to note the expected territorial changes mentioned by Fearndise et al. (2015).

Studies and field visits such as those by Macêdo et al. (2007) and Barrata (2011) point to the establishment of erosive processes in regions of the Tucuruí HPP reservoir (Figure 2). In this context, we sought to conduct direct and indirect erodibility assessments, based on empirical formulations and laboratory simulations of erosive processes performed on samples from the three soil formations in the reservoir área.

Gorge with accelerated erosion process observed by Macêdo et al. (2007).



Interrelation of the reservoir level with erosive processes near the left bank of the Tocantins River, Alcobaça Sustainable Development Reserve, verified by Barrata (2011).



Identification of processes on the margin of the reservoir in the municipality of Breu Branco and in the drainage area of the Caraipé region, observed by the authors.

Figure 2 - Manifestation of the accelerated erosive processes observed. Source: Adapted from Macêdo et al. (2007), Barrata (2011).

2. METHODOLOGY

Initially, field visits by terrestrial routes were made in the reservoir areas concerning the three pedological formations. Later, prospecting surveys were conducted using the auger and the manual digger, up to a depth of 2 meters, comparing the descriptive characteristics of the soil profile with those predicted for each soil typology, according to the Pedology Technical Manual and the Brazilian Soil Classification System - SiBCS, respectively made available by the IBGE (2007) and EMBRAPA (2018). It was possible to verify the compatibility of the pedological classification of the prospecting site with that estimated by the pedological map from the Urban Plan for the municipalities of Tucuruí and Breu Branco. In parallel to these activities, the main erosion processes in the vicinity were observed.

Such morphological characteristics produced a relief of lower altitude and slope on the left bank of the reservoir, while on the right bank the scenario is the opposite, as it could be verified in the field and through the altimetric analysis of maps made available in free virtual access bases, such as OpenStreetMap®.

It was also found, bibliographically, that according to Macêdo (2007) when computationally analyzing the slopes of areas considered as priorities of the reservoir for implementing interventionist measures, promoting the reduction of its erodibility and increased fertility, which varied from 0% at 30%, and seeking to simulate the field runoff phenomena with more reliability; that the sampling sites in the relief were established where pedological conditions were protected and in the middle or lower part of the slopes.

2.1. Sampling

The definition of the sampling locations was conducted considering the premise of pedological similarity among soils, erosive features, accessibility, and the absence of gravel. The

Beveled Cylinder established by ABNT NBR 9813 (2016) was used as a sampling method, with a continuous and slow hydraulic pile-driving system in trenches. Collection, storage, transport and immersion in porous stone for 3 days are shown in Figure 3
.

Two trenches – 8 m long, 0.7 m wide, and 0.5 m deep – were dug, from which 24 samples were collected, and also one sample from each end of the trenches, for characterization studies.

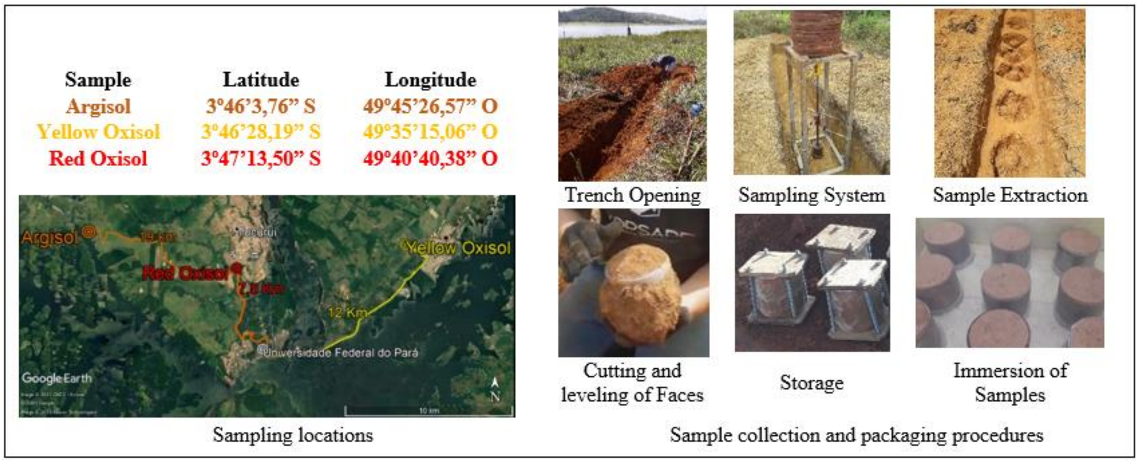


Figure 3 - Sampling locations and procedures. Source: The authors.

2.2. Characterization tests and complementary assessments

For the characterization of the soils, determinations were made for each sample collected at the ends of the trenches, totaling 4 tests per soil, performed according to the flowchart shown in Figure 4.

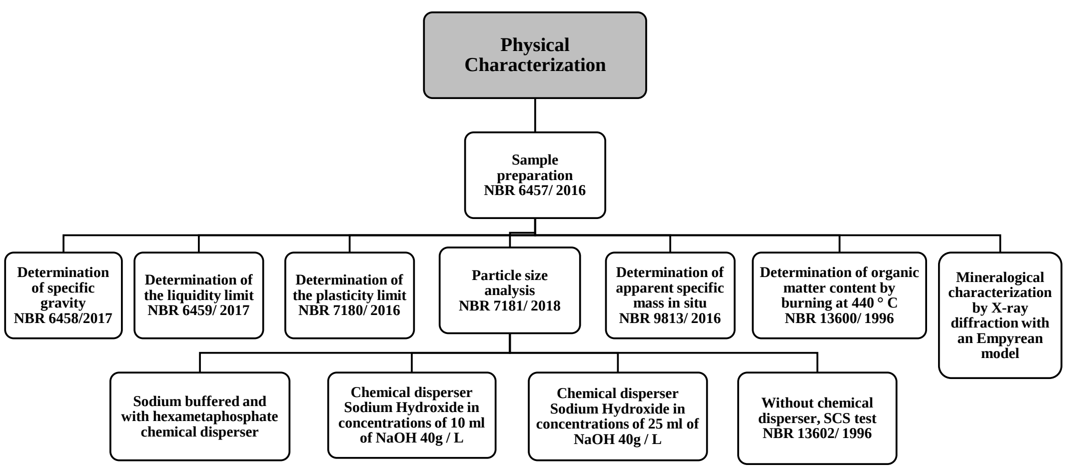


Figure 4 - Flowchart of sample characterization tests. Source: The authors.

For additional assessments regarding the hydraulic mechanical behavior of the samples, each test was performed 4 times, according to their respective methodologies:

• For the evaluation of the samples in the **Miniature, Compacted, Tropical** methodology, the **Disk Method** by Nogami and Villibor (1994) was used, with 5 shares and 4 measurements of penetration reading per disk.

The **Slaking Test** was used for analyzing the presence of soluble elements, the disposition of the gas phase and occurrence of expansive mineral clays. The samples were molded in a cubic format with edges of 60 mm of undisturbed soil and in humidity close to natural, according to the methodology described by Santos (1997). They were submitted to total and partial immersion, both with constant water levels.

2.3. Indirect determinations of erodibility

According to Araújo et al. (2011) and Correchel (2003), due to important developments over the years in the study of erodibility in several fields, it was possible to develop various methods of determining soil erodibility indirectly, based on several characteristics; among them, those using physical properties, according to Chart 1.

Chart 1 - Erosive features identified in the reservoir area. Source: Adapted from Araújo et al. Source: Adapted from Araújo et al. (2011) and Correchel (2003).

Authors	Use of properties	Indirect methods for determining the K-factor
Wischmeier, et al. (1971) method 1	Physical	**K= (% sand + % silt) / ((% clay) x 100),** where the K-Factor is given in (Mg ha h^{-1} MJ^{-1} mm^{-1}) and % sand, % silt and % clay represented the percentages of the respective granulometric fractions for horizon A.
Lombardi Neto & Bertoni (1975)	Physical	**K= ((% clay dispersed in water) / (%total clay) / ((%total clay) / (%equivalent humidity))**
Lombardi Neto & Bertoni (1975) modified by Lima et al (1990)	Physical	**K= (%silt + clay dispersed in water) / (%total silt + clay) /((% total clay) / (%equivalent humidity))**
Wischmeier et al. (1971) method 2	Physical	**K= {[2.1 (10^{-4}) (12-MO) $M^{1.14}$ + 3.25 (EST-2) + 2.5 (PER-3)] / 100} 0.1317** where: K is the estimated value for the K-factor, in Mg h $MJ^{-1}mm^{-1}$; M is the sum of the contents of silt (%) and very fine sand (%) multiplied by 100 minus the clay content (%), the granulometric analysis was performed using NaOH 1 mol L^{-1} as a dispersant; MO is the organic matter content (%); EST and PER are dimensionless codes, corresponding to the structure and soil permeability, respectively, as described in Wischmeier *et* al. (1971). The factor 0,1317 in the equation refers to the conversion of the original unit of K-factor to the international metric system, according to Foster et al. (1981).
Lima et al. (1990)	Physical	**K= {[2.1 (10^{-4}) (12-MO) $Ma^{1.14}$ + 3.25 (EST-2) + 2.5 (PER-3)] / 100} 0.1317** where: Ma is the sum of the contents of silt (%) and very fine sand (%) multiplied by 100 minus the clay content (%), the granulometric analysis was made only with water as dispersant. The other parameters of this equation are the same as those described for the original equation by Wischmeier et al. (1971) method 2.
Denardin (1990) method 2	Physical	**K= 0.00000748(M) + 0.00448059(PER) – 0.06311750(DMP) + 0,010396(REL**) where: DMP = weighted average particle diameter inferior to 2 mm; REL = content of the organic matter (%) divided by the percentage of particles with a diameter between 0,1 and 2 mm. In all cases, the granulometric analysis was performed using NaOH 1 mol L^{-1}.
Roloff & Denardin (1994) method 1	Physical	**K= 0.0049 PER + 0.0331 $Mm^{0,5}$** where: Mm is silt content (g g^{-1}) multiplied by the sum of silt and fine sand (g g^{-1}), the granulometric analysis was performed with NaOH 1 mol L^{-1}.

Bastos (1999), after extensively testing the erodibility of the metropolitan region of Porto Alegre/RS and its fundamental parameters, defined that the erodibility of soils subject to rainwater runoff is a function of the shear stresses on its surface. Thus, it can be expressed by K (g.cm-2.min./Pa), and classified as High when K > 0.1, Average when K is between 0.1 and 0.001 and Low when K < 0.001. Later, Mannigel et al. (2002), to better assess the variation in soil erodibility, established its classification in six levels, according to Chart 2.

Chart 2 - Levels of soil erodibility. Source: Adapted from Mannigel et al. (2002).

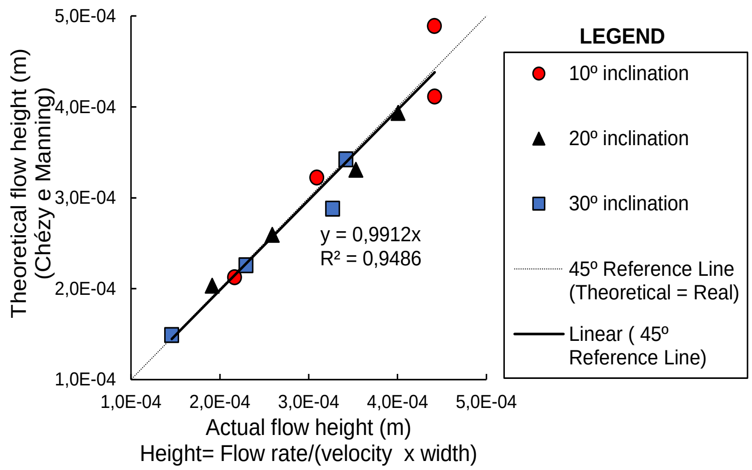
Classification	Erodibility Criterion $g.cm^{-2}.min./Pa$
Extremely high	> 0.100
Very high	0.075 a 0.100
High	0.050 a 0.075
Medium	0.025 a 0.050
Low	0.015 a 0.025
Very low	< 0.015

2.4. Simulated erosion test with the Inderbitzen device.

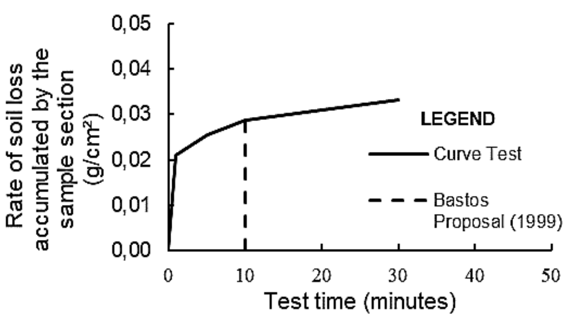
The Inderbitzen device (1961) consists of a hydraulic channel, where an unformed soil sample is attached close to the base of the channel and subsequently submitted to a controlled water flow, periodically registering the amount of material that is eroded and carried away, by a unit of time.

The hydraulic channel used in this study is made of acrylic material, supported on a rigid metallic structure, coated with gray surfactant paint from multi-sport courts, and from the brand Vertex. It is 150 cm long, 23.6 cm wide and 10 cm high. The 10.4 cm diameter beveled cylindrical sampler is positioned about 20 cm away from the end of the hydraulic channel, so that the surface of the sample is flush with the base, and in this way, allows the simulation of the runoff conditions. Figure 5 shows the Inderbitzen device, the verification of the flow characteristics, the graphical representation of the erosion test, and the determination of the erodibility K-factor by the addition of hydraulic shear stress.

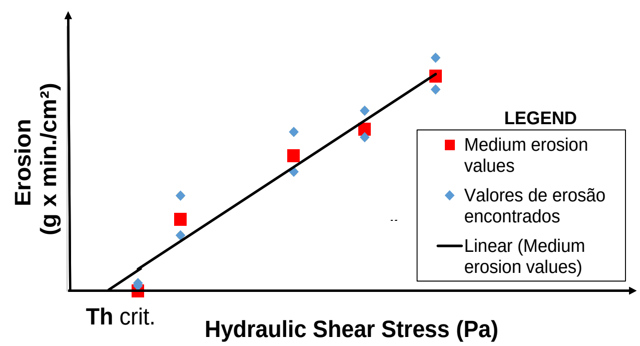
Inderbitzen device.



Verification of the flow conditions of the Inderbitzen device.



Representation of the average 10-minute erosion of a given hydraulic shear load.



Graphical representation of the erodibility K-factor.

Figure 5 - Erosive features identified in the reservoir area. Source: The authors.

This study followed the methodology by Bastos (1999), with soil samples from sites that present erosive processes in evolution, at the edges of the lake of the Tucuruí HPP, in the main existing soils, such as Argisol, Yellow Oxisol and Red-Yellow Oxisol. They were extracted at a depth of 0.5 m, evaluated in flood conditions with immersion in porous stone for at least 3 days, subjected to flow rates of 3.0 l/min with slopes of 10º, 20º, and 30º; 1.5 l/min and 4.5 l/min with an inclination of 20º; and 3.0 l/min with inclinations of 10º and 20º.

3. RESULTS AND DISCUSSIONS

The assessment of the results of the tests and methods conducted in this research is presented in the section Tests for the Characterization and Analysis of Erodibility.

The granulometric determination of each soil was carried out with samples from the ends of the trenches, defined based on 4 determinations. Besides, different test conditions were used, the % with the chemical dispersant (deflocculant) Sodium Hexametaphosphate, % of Sodium Hydroxide in concentrations of 10 and 25 ml of 0.04 g/l solution and % Without Deflocculant, resulting in the average values presented in Chart 3.

Chart 3 - Average particle size distributions of samples from each soil. Source: The authors.

Soil	**Condition of the test deflocculant**	**Clay Ø<0.002 mm (%)**	**Silt 0.002 - 0.06 mm (%)**	**Thin Sand 0.06-0.20 mm (%)**	**Medium Sand 0.2 - 0.6 mm (%)**	**Coarse Sand 0.6 - 2.0 mm (%)**
Argisol - PVA	Sodium Hexametaphosphate	68	11	12	7	2
	Sodium Hydroxide in 10 ml	67	10	14	7	2
	Sodium Hydroxide in 25 ml	66	8	18	6	2
	Without Deflocculant	9	36	27	25	2
Yellow Oxisol - LA	Sodium Hexametaphosphate	64	6	11	17	3
	Sodium Hydroxide in 10 ml	63	7	10	17	2
	Sodium Hydroxide in 25 ml	60	6	17	16	2
	Without Deflocculant	3	30	32	33	3
Red Oxisol - LV	Sodium Hexametaphosphate	63	33	4	1	1
	Sodium Hydroxide in 10 ml	61	35	3	1	0
	Sodium Hydroxide in 25 ml	43	51	5	1	0
	Without Deflocculant	0	42	31	25	2

The average of the granulometric determinations of the soil samples showed minor variation in dispersion effectiveness when observing the clay contents. When verified without deflocculant, a notable difference was found, showing that such materials have cementing agents in their constitution, which promote the formation of aggregations and contribute to the natural stability of soils. It should be noted that the Red Oxisol showed significant silt content, which, in the Disk Method, showed undesirable behaviors, such as volumetric expansion.

The Liquidity (LL) and Plasticity (LP) Limits point to a similarity of hydraulic mechanical behavior of the first two soils, distinguishing the Red Oxisol, but when checking the Plasticity Index (IP), we observed they are similar; that the Specific Mass points to typically weathered materials, with increments of heavier ones, such as oxides; that the Void Ratio and Total Porosity show structures with a great amount of voids; and that the Organic Matter Content shows elements without high organic quantities, according to Chart 4.

Chart 4 - Values of consistency limits, physical indices, and organic matter contente. Source: The authors.

Soil	**LL (%)**	**LP (%)**	**IP (%)**	**Average Specific Mass of Solids (g/cm³)**	**Specific Natural Dry Mass (g/cm³)**	**Average Void Ratio – e (cm³/cm³)**	**Total Porosity – n (cm³/cm³)**	**Average Organic Matter Content (%)**
Argisol – PVA	52.7	29.3	23.4	2.75	1.22	1.25	0.55	9.71
Yellow Oxisol – LA	51.4	26.5	24.8	2.68	1.10	1.43	0.58	9.12
Red Oxisol – LV	66.5	39.2	27.3	2.95	1.34	1.17	0.54	10.63

The mineralogical analysis through X-ray Diffraction indicated only low-activity, soluble, clay minerals such as Quartz, Anatase, Hematite, Aluminous Goethite, and Kaolinite, therefore, not presenting undesirable behaviors from the engineering point of view, such as expansions, if, according to Gomes and Toujaguez (2016), micaceous to muscovites occurred, as shown in Figure 6.

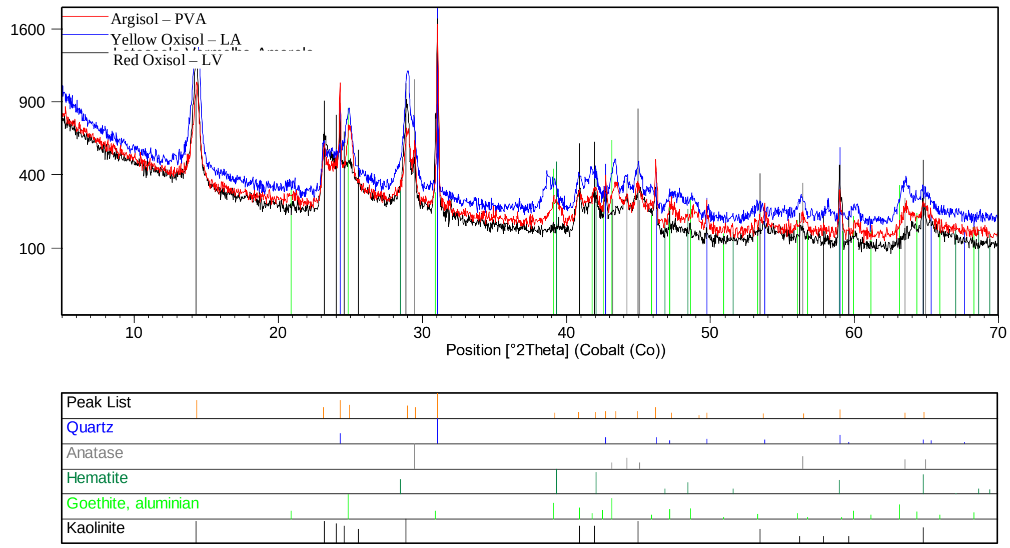


Figure 6 Mineralogical identification by X-ray diffraction. Source: The authors.

It should be noted that the minerals evidenced in this study are similar to those found by Theodoro (2009) when analyzing the sediments of the reservoir to test their reuse as a natural fertilizer, as shown in Figure 7.

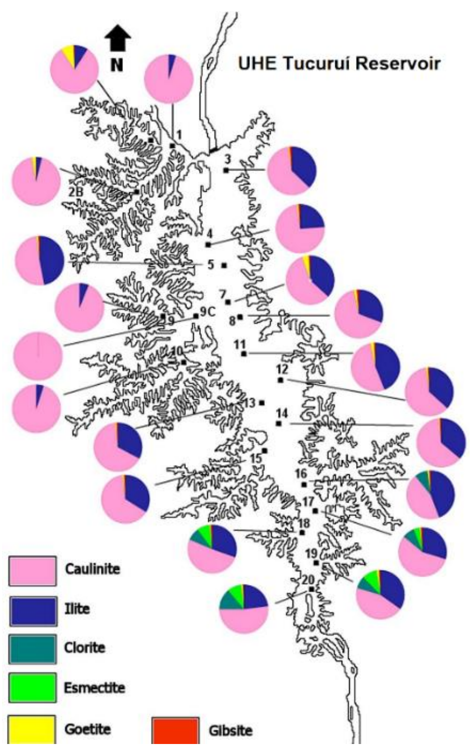


Figure 7 - Distribution of different types of clay from the sediments extracted in the reservoir. Source: Theodoro et al. (2009).

The data of contraction and penetration found by the Disk Method indicate, according to the MCT methodology, that the soil samples of the Argisol and Yellow Oxisol have the hydraulic mechanical behavior of a Lateritic soil, giving them low erodibility. As for the last one, it was found that, although the sample is classified pedologically as Red Lateritic soil, its hydraulic mechanical behavior, when under intense compaction, proved to be that of a Non-Lateritic material, with undesirable expansion (Figure 8), classified by the MCT as of Medium to High erodibility (Chart 5).

Argisol Disks - PVA | Yellow Oxisol Disks - LA | Red Oxisol Disks - LV

Figure 8 - Water reabsorption procedure in the disks used. Source: The authors.

Chart 5 - Determination of the group of the samples according to the MCT methodology. Fonte: Os autores.

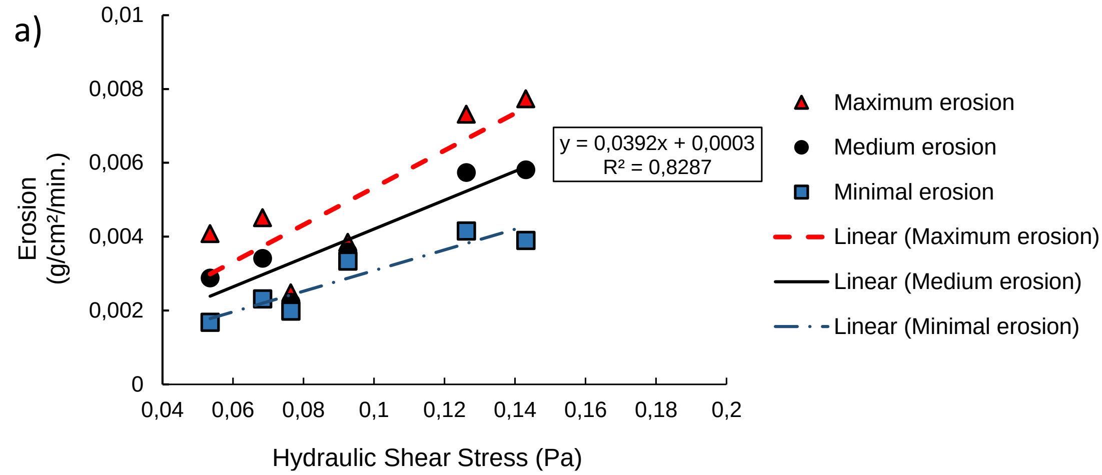
Soils	**Argisol - PVA**	**Yellow Oxisol - LA**	**Red Oxisol - LV**
Contraction (mm)	2.05	1.88	2.01
Penetration (mm)	0.40	0.72	2.58
Group M.C.T.	LG'	LG'	NG'
Erodibility	Low	Low	Medium to High
Erosion forms	Disaggregation	Disaggregation	Grooves and Disaggregation
Erosion level	Low	Low	High

The Slaking tests by partial and total immersion indicated good stability for the samples of Argisol and Yellow Oxisol, with very few slumps, however, the Red Oxisol showed a great variability of behavior, and mostly presented medium to high slumps and fractures, as shown in Figure 9.

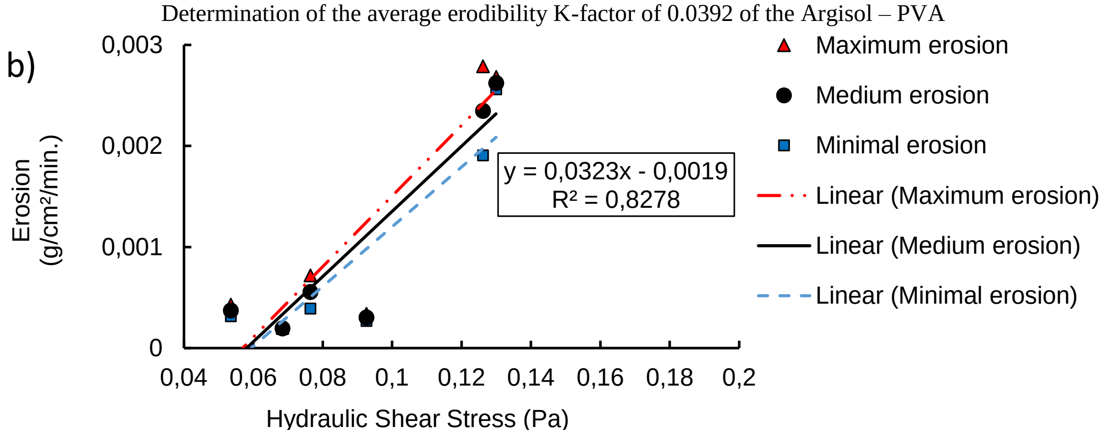
Argissol - PVA | Yellow Oxisol - LA | Red Oxisol - LV

Figure 9 - Slaking test with partial immersion.. Source: Os authors.

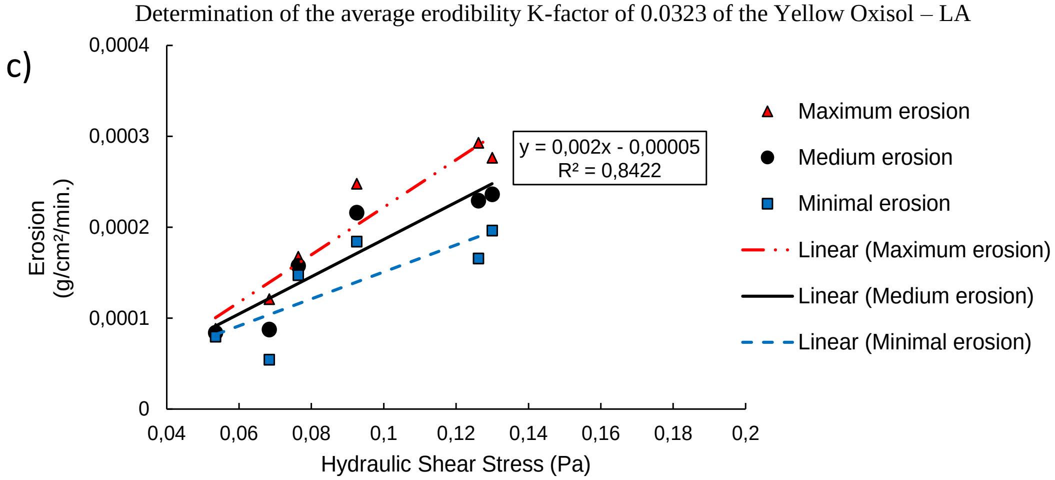
The analysis of the results of the successive erosion tests indicated that the determination of the Slope ratio of erosion by the increase of the Hydraulic Shear Stress, found for soil samples of Argisol, Yellow Oxisol, and Red Oxisol, were, respectively, 0.0392, 0.0323 and 0.002 g./cm²/min./Pa, as shown in Figures 10a, 10b, and 10c.



Determination of the average erodibility K-factor of 0.0392 of the Argisol – PVA



Determination of the average erodibility K-factor of 0.0323 of the Yellow Oxisol – LA



Determination of K-factor of 0.002 average erodibility of the Red Oxisol – LV

Figure 10 - Determination of the average erodibility K-factor of the samples. Source: The authors.

3.2. Erodibility analysis

The results of the characterization provided the means to conduct the determination of the erodibility K-factor with the indirect formulations, based on the physical characteristics of the samples. With their unit expressed in Mg ha h-1 MJ-1 mm-1 and converted to g/cm²/min./Pa with the factor of 5/3; and they have allowed the comparison with the experimental results obtained by the Inderbitzen device. They were also classified according to the levels of erodibility by Mannigel et al. (2002), in Figure 11.

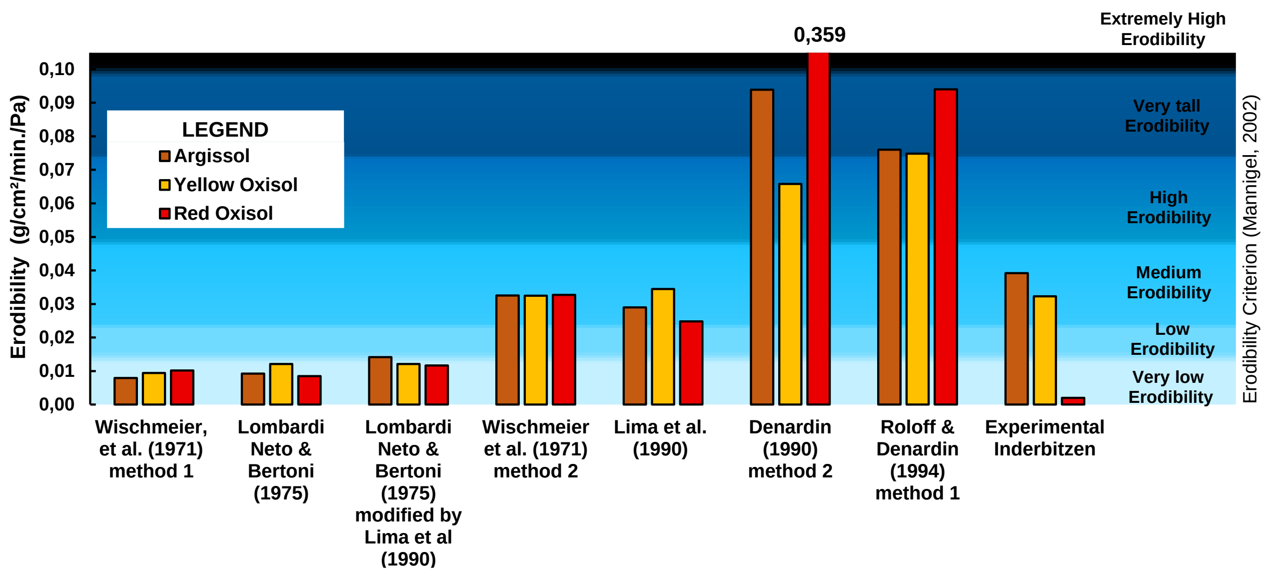


Figura 11 - Erodibility K-Factor classification determined by indirect formulations and found experimentally by the Inderbitzen device. Source: Os authors.

Using semi-empirical formulations, based on characterization properties may lead to very serious mistakes, from underestimating to overestimating soil erodibility. The formulations that were the most accurate compared to the experimental data were those by Wischmeier et al. (1971), method 2, and Lima et al. (1990). It is also recommended to conduct more tests with a larger number of samples from soils of different pedological classifications, for more comprehensive statements.

The measurement of erodibility with the Inderbitzen device shows, according to Mannigel et al. (2002), low erodibility for the Red Oxisol and medium erodibility for the Argisol and Yellow Oxisol, which are similar to some soils from Minas Gerais studied by Stephan (2010), and from Rio Grande do Sul, studied by Bastos (1999). However, for deeper conclusions, evaluations with other testing systems are recommended, such as those by Briaud et al. (2019), and the experimental stations described by Xavier et al. (2016).

The Slacking test pointed to high levels of stability for the Argisol and the Yellow Oxisol, demonstrating the effectiveness of the aggregation of the particles evidenced in the granulometric measurements, with and without the use of deflocculant as a chemical disperser. However, although the Red Oxisol also presents such aggregation, the significant amount of silt-sized particles gives it a sensitivity, making it susceptible to disaggregation, fractures, and expansions, as verified by the Disk Method.

The Disk Method pointed out that, in extreme conditions of compaction, all samples showed high levels of contraction. Because of the high clay content, however, when subjected to water reabsorption, only the Oxisol underwent expansion due to significant levels of silt, indicating the possibility of adverse behaviors in the area where it is present.

Thus, it can be concluded that depending on the techniques performed, the soils analyzed that form the reservoir area of the Tucuruí HPP, are of low to medium erodibility, which demands attention to their use and occupation, suggesting maintenance of their surface coverage. For soils of medium erodibility, and for the Oxisol, it is recommended to avoid uses that may provoke its destabilization and compaction.

4. FINAL CONSIDERATIONS

Through this research, it was found that the samples of the analyzed soils; even with fine particles and less weight of their own, compared to granular soils; had high rates of plasticity, giving them aggregation and low to medium rates of erodibility. Despite being poorly erodible in their natural condition, when under strong compaction they can become expandable and favor the increase of erodibility. Therefore, it is indicated that the agricultural activities favor crops that maintain the superficial coverage of the areas of the Argisol and Yellow Oxisol, and the prevention of uses that can cause disruption and compaction of the Red Oxisol.

Regarding the physiographic characteristics of the reservoir, it was found that the factor of greatest difficulty, both for its management and support of academic and professional research, is the territorial extension. However, studies such as those by Barrata (2011), and field analyzes conducted in this research, point to the significant influence of the variation of level in the regions of the edge of the reservoir. Such influence allows, in certain locations, the establishment of erosive processes that cause significant environmental damage. This information may guide the choice of spots for monitoring and future work.

Despite the small territorial extension visited, it is noted that the reservoir has a low number of erosive features developing outside its borders. However, many of the land uses and occupations are still recent, highlighting the importance of continuous care and monitoring.

In order to expand and complement the research, it is suggested for future work to conduct computational modeling and assessment of Susceptibility to laminar erosion; perform a survey of the conditions of all flow contributors in the drainage area of the Tucuruí HPP reservoir; promote studies and solutions to control or mitigate the impact of changes in the level at the edges of the Tucuruí HPP reservoir; use the methodology and equipment of this research to evaluate the soil erodibility indexes in samples of different pedological characteristics from the municipalities that constitute the reservoir and propose specific management and monitoring plans for each soil type and region under the influence area of the Tucuruí HPP.

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