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## ***Characterization of the Reservoirs in the Crateús Hinterland Basin According to the Dam Safety Law 12,334/2010 Using Satellite Images***

**CARACTERIZAÇÃO DOS RESERVATÓRIOS DA BACIA DOS SERTÕES DE CRATEÚS SEGUNDO A LEI DE SEGURANÇA DE BARRAGENS 12.334/2010 UTILIZANDO IMAGENS DE SATÉLITES**

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**Abstract:** This study aims to characterize earth dams in the Sertões de Crateús Basin in order to classify them according to established legal criteria. Based on water surface mapping provided by FUNCEME and high-resolution imagery from Google Earth, 21 natural reservoirs, 1 concrete dam, 86 artificial lakes, and 282 earth dams were identified. The analysis was conducted using Geographic Information System (GIS) tools, specifically ArcGIS, which provided data on location, area, perimeter, and slope. Based on simplified methodologies proposed by Araújo et al. (2012), the heights and storage volumes of the 282 earth dams were estimated. Validation was performed by comparing data from 10 known reservoirs with the estimated values, resulting in coefficients of determination of 0.999 for volume and 0.992 for height, demonstrating a strong agreement between observed and estimated data. The dams were classified according to Law No. 12,334/2010 (later updated by Law No. 14,066/2020), considering factors such as height, reservoir volume, Risk Category (CRI), and Associated Potential Damage (DPA). Of the 282 analyzed dams, 55 met at least one legal criterion. However, only 9 are monitored by government authorities, while 46 are privately owned dams with no available information, highlighting a concerning regulatory gap that increases associated risks.

**Keywords:** Legislation. GIS. Dams.

**Resumo:** Este estudo visa caracterizar as barragens de terra na Bacia dos Sertões de Crateús, a fim de enquadrá-las aos critérios legais estabelecidos. Por meio do mapeamento de espelhos d'água da FUNCEME e imagens do Google Earth, foram identificados 21 reservatórios naturais, 1 barragem de concreto, 86 lagos artificiais e 282 barragens de terra. A análise foi realizada utilizando ferramentas de Sistema de Informação Geográfica (SIG), especificamente o ArcGIS, que forneceu informações sobre localização, área, perímetro e declividade. Baseando-se em metodologias simplificadas de Araújo et al. (2012), foram estimadas as alturas e volumes das 282 barragens de terra. A validação consistiu na comparação de dados de 10 reservatórios conhecidos com os dados estimados, resultando em coeficientes de determinação de 0,999 para volumes e 0,992 para alturas, o que demonstra uma boa aproximação entre os dados. As barragens foram classificadas de acordo com a Lei 12.334/2010 (posteriormente 14.066/2020), considerando fatores como altura, volume dos reservatórios, Categoria de Risco (CRI) e Dano Potencial Associado (DPA). Dos 282 barramentos analisados, 55 atenderam a pelo menos um critério legal. Contudo, apenas 9 são monitorados pelo governo, enquanto 46 são barramentos particulares sem qualquer informação disponível, evidenciando um preocupante vazio regulatório que amplifica os riscos.

**Palavras-chave:** Legislação; SIG; Barragens.

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## 1. Introduction

Dams play a significant social role in ensuring water supply and water security for various populations, both nationally and globally, especially in regions with restricted water availability, such as the semi-arid region of northeastern Brazil (SAMPAIO, 2014). The Brazilian semi-arid region has a history of droughts and is known for the construction of reservoirs and dams, as well as for discussions regarding the role of water infrastructure in development and its interrelationships with the so-called "drought industry" (FERREIRA, 2020). The combination of below-average rainfall and extreme drought events recorded in recent years resulted in a water crisis that deeply affected several regions of Brazil, particularly the semi-arid region, between 2012 and 2017 (Cunha et al., 2019, p. 7).

Relying on watercourses during periods of high temperatures and intense evaporation can be risky and unfeasible. Therefore, it is fundamental to construct dams in rivers or streams to allow for water storage, ensuring access to this vital resource outside the rainy season (CBDB, 2019). The benefits of a dam extend to the entire population, providing water supply for human and industrial consumption, irrigation, hydroelectric power generation, and flow regulation, thus mitigating the impacts of droughts and floods (BIZIAMI, 2023, p. 13). The construction of reservoirs has become a measure for coping with problems related to the semi-arid climate, which is characterized by irregular and poorly distributed rainfall patterns throughout the year. Although these structures offer many benefits, they can also cause social and environmental impacts in the areas where they are implemented. This includes ecosystem alteration, community displacement, and the occurrence of induced seismicity (ANA, 2020, p. 11).

In a study conducted by Aguiar (2014), it was observed that private owners built dams without any technical knowledge on the subject or detailed investigations of the region, which increased the insecurity of the entire downstream population. The problem with the construction of a high number of private dams is the lack of information available to the State Public Authorities, given that data collection is of strategic importance considering the risks that reservoirs represent to infrastructure projects, cities, and the population (Martins et al. 2007, p. 1).

Some countries have already expressed concern regarding the prolonged use of dams, making the safety of these structures a priority issue. However, few possess specific legislation focused on dam safety. Among the countries that have adopted their own regulations, European nations such as Portugal, the United Kingdom, and Spain stand out, in addition to the United States and Canada, which have established their own legal standards (ZATELLI, 2019).

In this context of legal and normative aspects, and with the objective of satisfying the requirements of dam behavior regarding operational, structural, and environmental aspects—aiming to prevent accidents and/or mitigate their consequences throughout the lifespan of the structure—the Dam Safety Law 12.334/2010 was elaborated in Brazil. The lack of data on dams hinders oversight, which is the responsibility of the Secretariat of Water Resources (SRH) or the National Water Agency (ANA) in the case of federal rivers. These agencies face a shortage of information and personnel for inspection, especially regarding dams on private properties. The SRH, for example, does not have sufficient and updated data on the reservoirs of the Sertões de Crateús Basin. Dam Safety Reports (RSB) from ANA show that accidents involving water dams in Ceará are becoming more frequent (RSB, 2017).

Thus, it becomes relevant to obtain information capable of characterizing these reservoirs, particularly those that are not monitored, in accordance with the Dam Safety Law 12.334/2010, as a means of preventing accidents and risks posed by the construction of these barriers. This information gap, combined with the difficulty of enforcement, creates a significant regulatory void, amplifying structural safety risks and fostering an environment prone to conflicts over water use, particularly under increasing climate pressures. The central question of this study is: How can the dams in the Sertões de Crateús Basin be qualified according to the Dam Safety Law 12.334/2010?

## 2. Methodology

This work presents an exploratory study on the characterization of earth dams in the Sertões de Crateús Basin. The methodology adopted in this study consisted of the steps illustrated in Figure 1, which enabled the fulfillment of the proposed objectives.

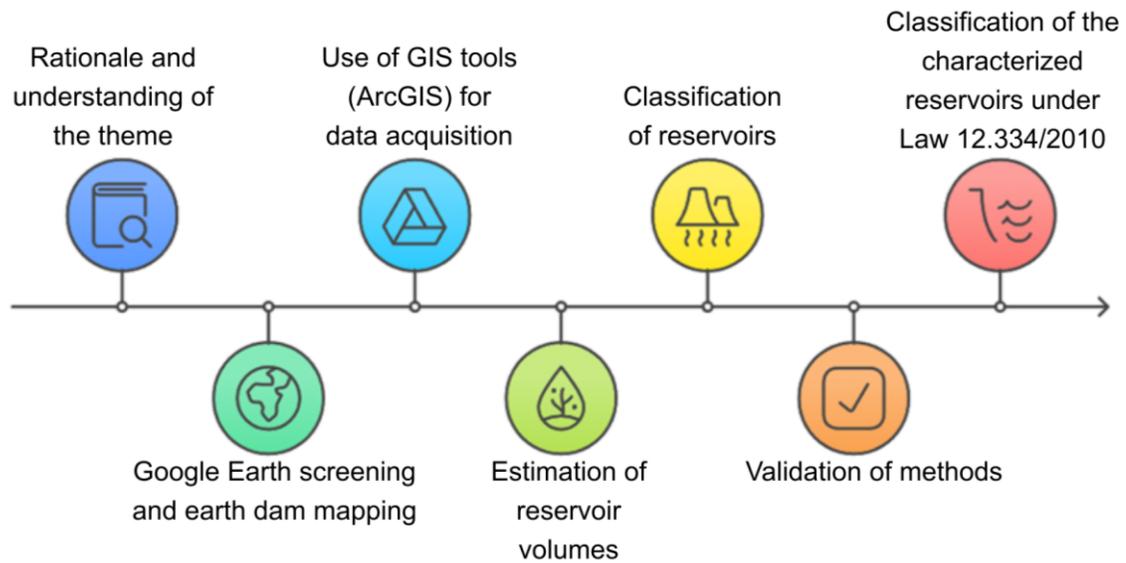


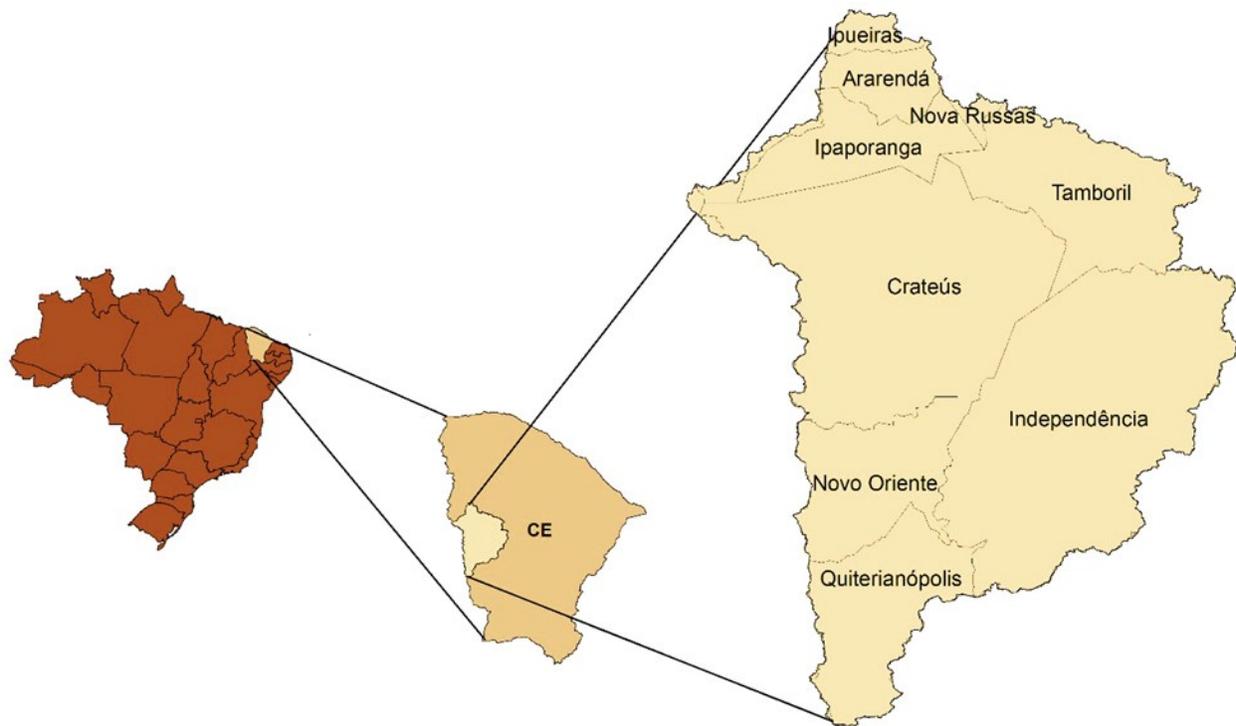
Figure 1 – Research stages  
Source: Authors (2026).

## 2.1 Study area

The Sertões de Crateús region is characterized by low average annual rainfall regimes, irregular precipitation combined with high evaporation rates, and large rural areas dedicated to agropastoral activities. Additionally, it has a semi-arid climate with average thermal conditions exceeding 26 °C (SEBRAE, 2019).

The study area comprises the territory of the Sertões de Crateús hydrographic basin, the main basin in the region. This area is located in the State of Ceará and covers 10,821 km<sup>2</sup>, encompassing the drainage network of the Poti River (SRH, 2019).

Furthermore, according to the Secretariat of Water Resources (SRH), this basin has a surface water storage capacity of 446,685,647 m<sup>3</sup> and a total of 10 reservoirs monitored by COGERH, 9 of which have earth dams and 1 is a concrete dam. The Sertões de Crateús Basin includes contributions from 9 municipalities (Figure 2): Ararendá, Ipaporanga, Crateús, Independência, Novo Oriente, Quiterianópolis, and parts of the territories of Tamboril, Nova Russas, and Ipueiras.



*Figure 2 - Location of the Sertões de Crateús Basin and Its Contributing Municipalities*  
*Source: Authors (2026).*

## 2.2 Data acquisition

This study estimated the number of earth dams in the Sertões de Crateús Basin based on satellite imagery. Once the study objectives were established, a bibliographic research was conducted to obtain files where data and information were available. Through screening in Google Earth, the water surface samples were narrowed down to reservoirs with areas larger than 5 hectares (as these represent larger and more significant reservoirs) that possessed earth dams. Natural reservoirs, concrete dams, and reservoirs with the appearance of artificial lakes—specifically those where satellite imagery did not indicate the existence of a dam structure—were excluded.

To obtain the water accumulation area, Geographic Information System (GIS) tools (ArcGIS 10.3) were used to process a shapefile containing the surface water bodies of the study area, provided by the Cearense Foundation for Meteorology and Water Resources (FUNCEME). From this, it was possible to obtain the area, perimeter, and geographic location of all water surfaces in the basin.

A total of 390 water surfaces larger than 5 hectares were identified, constituting a more significant sample for volume estimation. Of this total, 21 are natural reservoirs, 1 has a concrete dam (Batalhão Reservoir), and 86 have the appearance of artificial lakes, reducing the sample to 282 potential reservoirs with earth dams distributed among the municipalities within the basin (Figure 3). It is noteworthy that one of the main limitations of this stage is that the sample screening is

based on the resolution of satellite images and the personal judgment of the authors regarding what represents an earth dam in Google Earth.

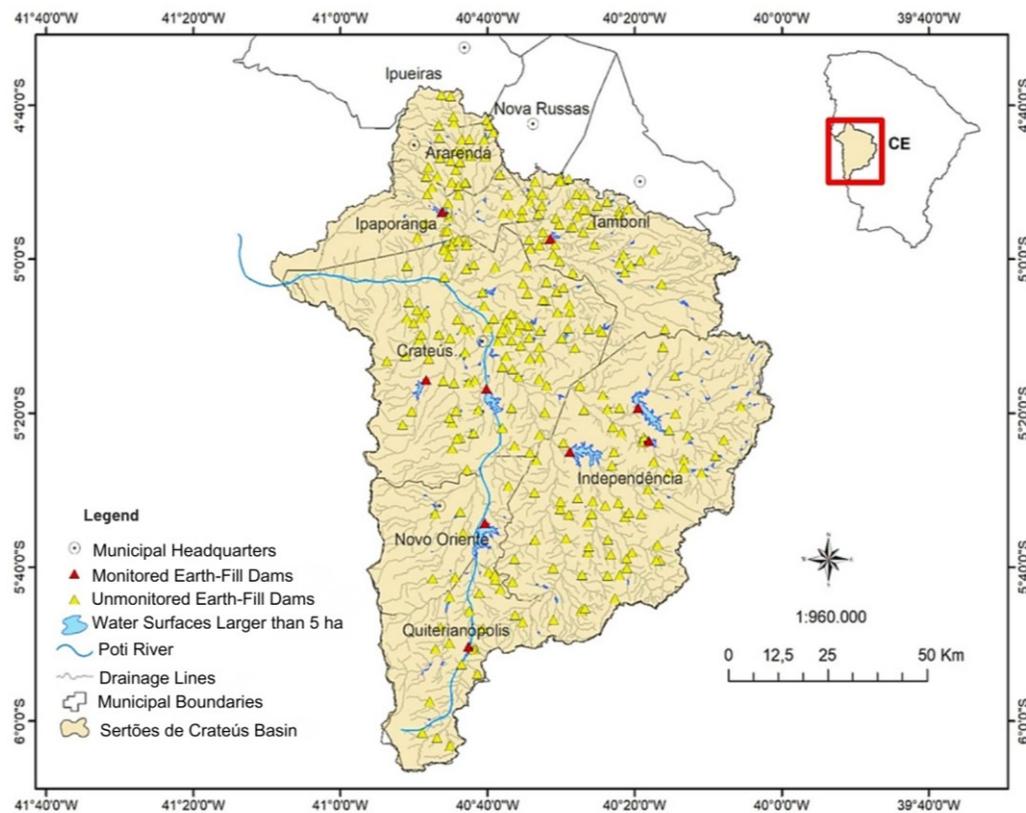


Figure 3 - Location of Earth-Fill Dams in the Sertões de Crateús Basin  
Source: Authors (2026).

### 2.3 Dam height

The calculation of dam heights is a process that depends on determining the maximum depth of the reservoirs. One of the methodological mechanisms used to determine this aspect is the use of remote sensing through a Digital Elevation Model (DEM) from the SRTM (Shuttle Radar Topography Mission) project, with a spatial resolution of 92 meters, providing information with a satisfactory precision level conducted by NASA (2011). In this way, it is possible to obtain the slope of the downstream embankments of the dams in this study, based on the premise that the slope of the hillside remains the same throughout its profile. Thus, the slope can be obtained by processing this model through the ArcMap software (ArcGIS 10.3) using the Slope tool (Spatial Analyst Tools < Surface < Slope) (ARAÚJO *et al.*, 2012). Furthermore, according to techniques used in studies by Fernandes (2018), the horizontal length of the downstream slopes of the 282 earth dams in the Sertões de Crateús Basin was measured using the Ruler tool in Google Earth. Consequently, it was possible to estimate the height of the dams in this study by relating the measured horizontal length to the slope of the downstream embankments of the basin. The height of the dams was obtained by isolating the vertical distance (DV) term in the slope expression, shown below:

$$D = \frac{DV}{DH} \times 100 \quad (\text{eq. 1})$$

Where:

D: the downstream slope of the dam, expressed as a percentage (%);

DV: the vertical height difference;

DH: the horizontal distance;

## 2.4 Araújo *et al.* (2012) Méthod

Simplified methodologies such as the one presented in this study are widely used because they provide results in a simple and rapid manner, serving as a guideline for identifying the characteristics of reservoirs in the Sertões de Crateús Basin (SHOURIAN *et al.*, 2008). Thus, the equation used to calculate reservoir volumes is based on the studies of Molle (1994a):

$$V = \frac{A \times H}{\alpha} \quad (\text{eq. 2})$$

Where:

V: reservoir volume;

A: water surface area of the reservoir;

$\alpha$ : reservoir shape coefficient;

H: maximum depth of the reservoir;

This methodology has two limitations. The first is related to the applied shape factor, since it depends on the slope geometry of the valley profiles in which the reservoir is located (Araújo *et al.*, 2012). Molle (1994a) states that three types of natural valley profiles exist: straight, concave, and convex. However, for simplification purposes, only the average (straight) profile was considered and applied to all reservoirs within the study area. Initially, the single shape factor proposed by Molle (1994a), with a value of 2.70 ( $\alpha = 2.70$ ), was adopted. Studies such as Araújo *et al.* (2012), conducted in the Banabuiú Basin, and Fernandes (2018), in the Lower Jaguaribe sub-basin, also applied the initial shape factor of 2.70 suggested by Molle (1994a) and obtained satisfactory results in their analyses.

The second limitation is associated with the lack of reliable information regarding the actual maximum depth of each reservoir. Therefore, an estimated survey of this parameter is required. Geographic Information System (GIS) tools were employed to identify terrain slope and improve the accuracy of the computed results presented in this study. Small and medium-sized reservoirs may exhibit variations in the shape factor ( $\alpha$ ), requiring calibration of these values. Based on bathymetric surveys conducted by COGERH in nine earth-fill dams monitored by public authorities (Figure 6), information on storage capacity (volume) and maximum dam height was obtained. By isolating the  $\alpha$  factor from Molle's (1994a) equation, calibrated values for the applied method can be derived.

According to Araújo *et al.* (2012), reservoirs with water surface areas smaller than 1,000,000 m<sup>2</sup> are classified as small reservoirs, whereas those exceeding this threshold are classified as medium-sized reservoirs. However, for the Sertões de Crateús Basin, shape factors are only available for medium- to large-sized reservoirs (Table 1).

Table 1 – Shape factor ( $\alpha$ ) for different reservoirs in the Sertões de Crateús Basin

$\alpha$ Medium Reservoir			$\alpha$ Large Reservoir		
Surface Area > 1 milhão m <sup>2</sup>			Surface Area > 10 milhões m <sup>2</sup>		
Reservoir	Area (m <sup>2</sup> )	$\alpha$	Reservoir	Area (m <sup>2</sup> )	$\alpha$
SUCCESSO	1.642.831,85	3,179	JABURU II	15.556.010,96	2,430

COLINA	1.073.877,79	3,004	BARRA VELHA	17.649.708,37	2,847
REALEJO	4.343.772,86	2,891	FLOR DO CAMPO	15.050.586,56	3,141
CUPIM	1.625.568,36	3,392	CARNAUBAL	10.303.510,38	2,632
Mean		3,116	Mean		2,763
Standard Deviation		0,218	Standard Deviation		0,304
Variation		0,048	Variation		0,092

*Source: Authors (2026).*

Thus, for the calibration of the form factors of reservoirs classified as small, which constitute the majority of the reservoirs in the basin, it is necessary to adopt the values suggested by Araújo *et al.* (2012). The authors recommend using a form factor of 4.740 ( $\alpha = 4.740$ ) for small reservoirs (surface area < 1,000,000 m<sup>2</sup>) and a form factor of 2.095 ( $\alpha = 2.095$ ) for medium reservoirs (surface area > 1,000,000 m<sup>2</sup>). These form factor values were also applied to the reservoirs of the Lower Jaguaribe sub-basin in the study conducted by Fernandes (2018), yielding satisfactory results. Subsequently, it was possible to recalculate the reservoir volumes using the calibrated form factors ( $\alpha$ ). Next, we sought to establish a linear relationship between the surface areas of the dams and their respective storage capacities, with both being plotted on a logarithmic scale.

## 2.5 Reservoir classification

Once the estimated volumes and depths for the 282 reservoirs in this study were determined, and aiming to improve the discrimination process of the reservoirs comprising the basin, a new filtering step became necessary. Using the classification exemplified in the study by Molle (1994b), it is possible to perform a new filtering of the reservoirs in the Sertões de Crateús Basin based on their storage capacity, considering that:

Small Earth Dams (Barreiros): Have estimated volumes of less than 300,000 m<sup>3</sup>;

Small Reservoirs: Have estimated volumes greater than 300,000 m<sup>3</sup>;

Medium Reservoirs: Have estimated volumes between 3,000,000 m<sup>3</sup> and 10,000,000 m<sup>3</sup>;

Large Reservoirs: Have estimated volumes greater than 10,000,000 m<sup>3</sup>.

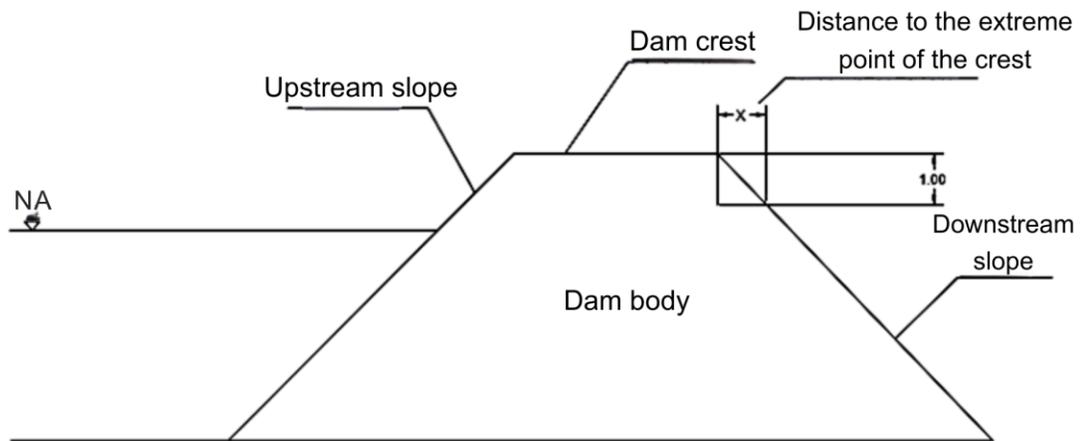
## 2.6 Method Validation

The validation of the methods employed in this study consists of comparing the results obtained for the estimated reservoir volumes and dam heights—based on the methodology described by Araújo *et al.* (2012)—with information from the technical data sheets of the monitored reservoirs in the Sertões de Crateús Basin, available on the Hydrological Portal of Ceará, as well as with field surveys conducted at the São Francisco Reservoir dam in the municipality of Crateús (Figure 4).



*Figure 4 – São Francisco Reservoir Dam, Cratêus - CE  
Source: Authors (2026).*

During the field survey, the height of the São Francisco Reservoir dam was determined using the downstream slope inclination method applied by Fernandes (2018). This parameter was obtained by establishing a proportion in which a vertical height of 1 (one) meter was fixed between the downstream slope and the highest point of the dam crest. Subsequently, the horizontal distance from this point to the outermost edge of the crest was measured in order to determine the actual slope inclination and the dam height (Figure 5).



*Figura 5 - Cross-section of a dam illustrating the downstream slope inclination method  
Source: Adapted from Fernandes (2018).*

## 2.7 Classification under law 14.066/2020

According to the Dam Safety Law (Law No. 14.066/2020), a dam falls under the provisions of this legislation if it meets at least one of the following criteria:

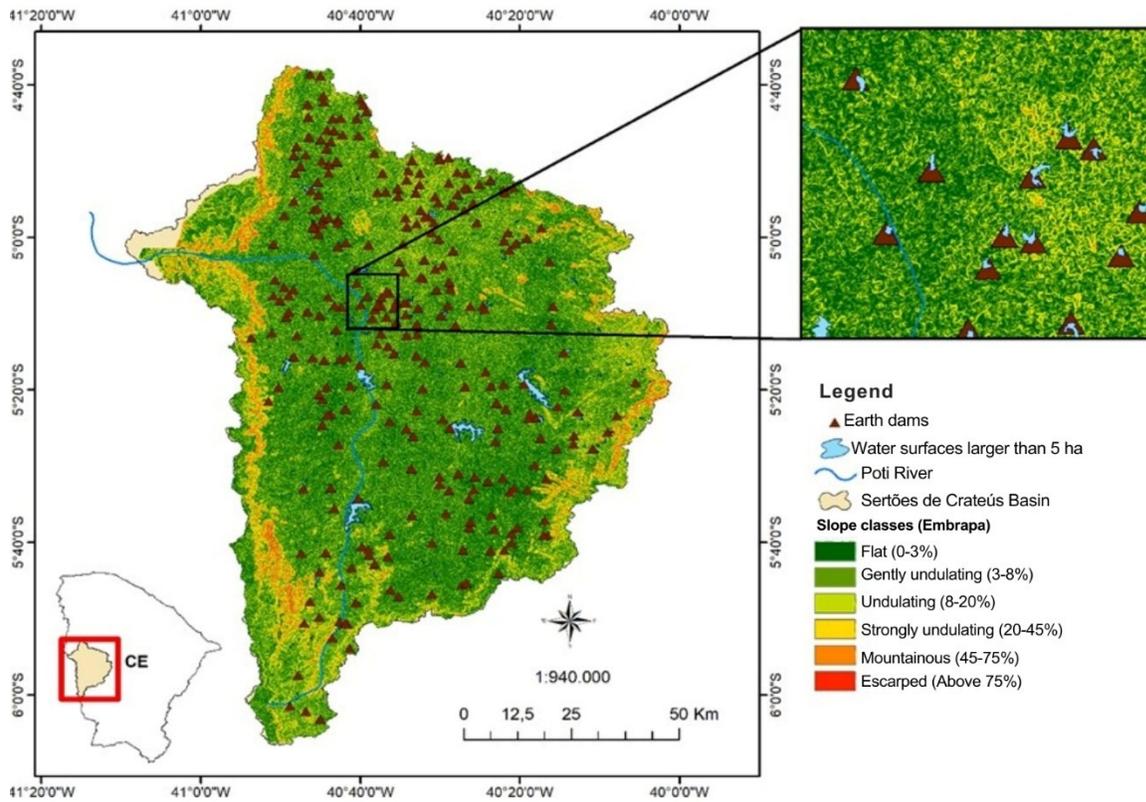
- **Height of the dam structure**, measured from the lowest point of the foundation to the crest, greater than or equal to 15 meters;
- **Total reservoir capacity** greater than or equal to 3,000,000 cubic meters;
- **Reservoirs containing hazardous waste**;
- **Medium or high Associated Potential Damage (DPA)** category, in economic, social, environmental terms, or regarding the loss of human life;
- **High Risk Category (CRI)**, at the discretion of the supervisory agency.

As described in the legislation, the classification by Risk Category (CRI - *Categoria de Risco*) into high, medium, or low considers the technical characteristics of the dam, its state of conservation, and compliance with the Dam Safety Plan (PSB - *Plano de Segurança da Barragem*). Furthermore, the classification by Associated Potential Damage (DPA - *Dano Potencial Associado*) category is based on economic, social, and environmental impacts, as well as the risk of loss of human life. To classify the dams, an individual analysis of the estimated heights and volumes of each reservoir in the basin was conducted, resulting in the qualification of the dams in accordance with Law No. 14.066/2020.

## 3. Results and Discussion

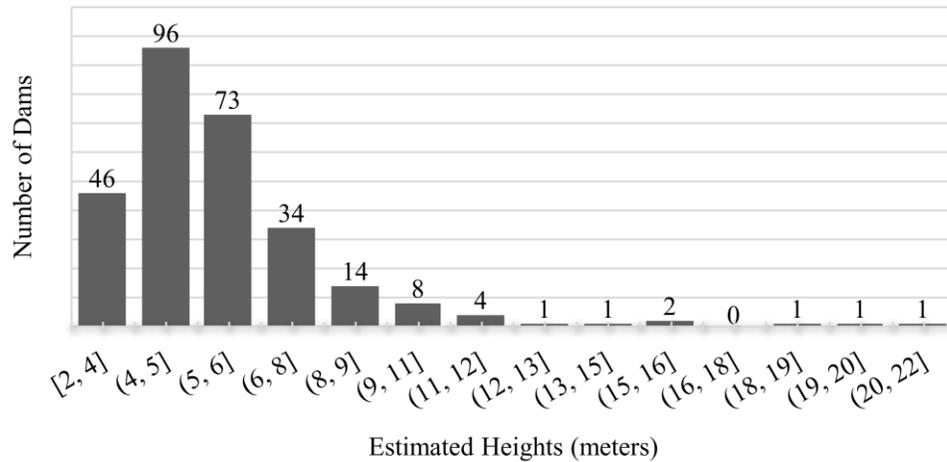
### 3.1 Estimated Heights

The results for the estimation of dam heights depend on determining the inclination of the downstream slopes. Consequently, by magnifying an arbitrary region of the slope map for the Sertões de Crateús Basin (Figure 6), it is possible to observe that, near the dams, there are regions classified as 'Strongly Undulating' (*Forte Ondulado*) according to Embrapa criteria. These areas exhibit slope gradients ranging from 20% to 45% and are found in the vicinity of all the dams in the sample.



*Figure 6 - Slope Map of the Sertões de Crateús Basin*  
 Source: Authors (2026).

The application of the technique proposed by Fernandes (2018), coupled with the recommendations from Araújo et al. (2012), yielded satisfactory results. This approach offers advantages such as the ease of data acquisition and the low cost of the process, given that Google Earth is a freely available online tool. Graph 1 illustrates the estimated height values obtained for the 282 earth dams in the sample.



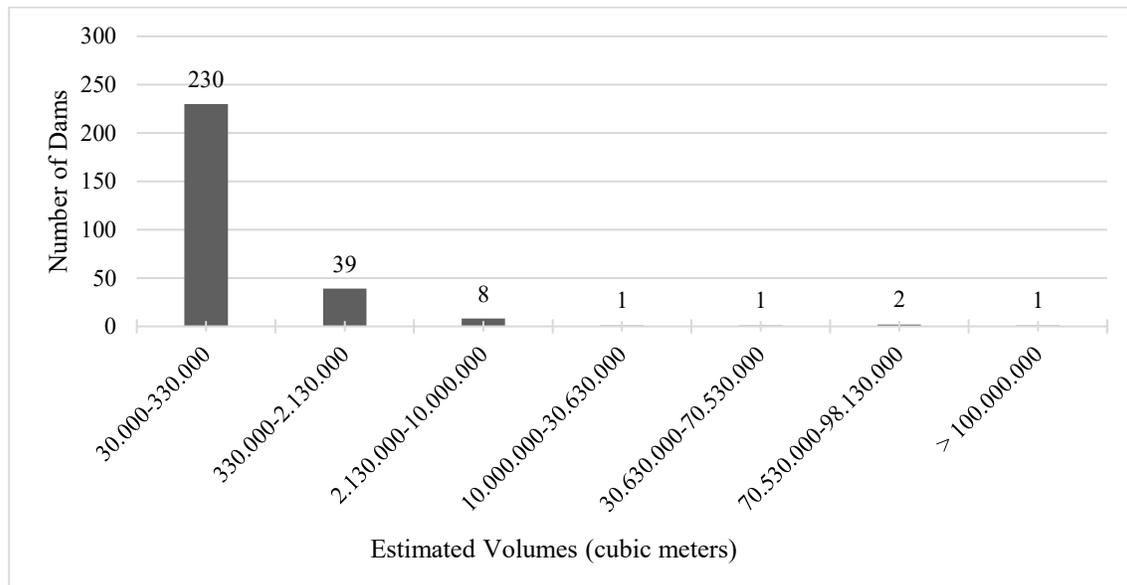
*Graph 1 - Variation in the estimated heights of the earth-fill dams in the sample*  
 Source: Authors (2026).

It can be observed that the reservoirs in the sample have dams with an average height of 5.63 meters. As shown in Graph 1, the most frequent reservoirs feature dam heights ranging from 4 to 6 meters. Finally, the dispersion of the analyzed data yielded a standard deviation of 2.56 meters.

### 3.2 Estimated Volumes

The results obtained from the volume estimation for the Sertões de Crateús Basin are presented in Graph 2. It is evident that the analyzed sample is highly heterogeneous, as a significant portion of the reservoirs falls within the storage capacity range of 30,000 m<sup>3</sup> to 330,000 m<sup>3</sup>, in contrast to others that reach millions of cubic meters. Consequently, there are reservoirs with substantial volumes exceeding 10,000,000 m<sup>3</sup>, and some even surpassing 100,000,000 m<sup>3</sup>. The estimated volumes corroborate the discussion presented by Molle (1994b). The author reports that in water-restricted regions, Public Authorities have focused on constructing large reservoirs as a result of public policies aimed at combating droughts. Preceding these initiatives, however, a vast number of small reservoirs were built by private individuals—a practice that persists today.

Consequently, Molle (1994b) argues that the construction of small-scale dams is a colonial legacy that enabled farmers to cultivate their land and raise livestock. Over the centuries, the local population of the semi-arid region (sertanejos), relying on practical sense, realized that this was the only means to compensate for the absence of perennial rivers, thereby initiating the construction of these small dams.



*Graph 2 - Variation in the Estimated Volumes of the Sample Reservoirs*  
 Source: Authors (2026).

Additional results indicate a mean reservoir volume of 1,776,080.82 m<sup>3</sup>, with a standard deviation of 11,123,980.78 m<sup>3</sup>. This high standard deviation demonstrates that the data points are dispersed across a broad range of values, characterizing a highly heterogeneous sample.

### 3.3 Reservoir classification

The Sertões de Crateús Basin has proven to be highly heterogeneous thus far, presenting a wide range of estimated values for both volumes and heights. Therefore, the reservoirs were classified based on the estimated capacity of the 282 potential dams in this study. This classification, based on Molle (1994b), aims to provide a better understanding of the basin and the most widespread water impoundment technique in the region.

The Figure 7 illustrates the location of the dams within the basin and their respective classifications: Small Earth Dams / *Barreiros* (Vol. < 300,000 m<sup>3</sup>); Small Reservoirs (300,000 m<sup>3</sup> < Vol. < 3,000,000 m<sup>3</sup>); Medium Reservoirs (3,000,000 m<sup>3</sup> < Vol. < 10,000,000 m<sup>3</sup>); and Large Reservoirs (Vol. > 10,000,000 m<sup>3</sup>).

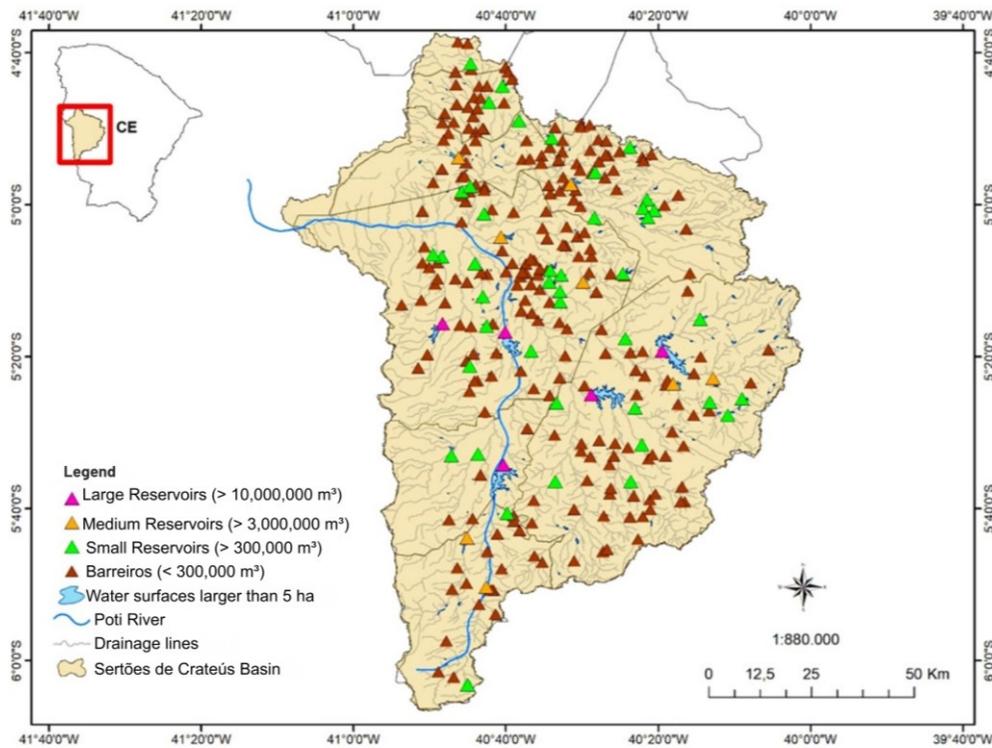


Figure 7 - Location of Barreiros and Small, Medium, and Large Reservoirs  
 Source: Authors (2026).

The results of this grouping are presented in Table 2. It is noteworthy that this categorization confirms the existence of a large number of small dams, also known as barreiros, which are rudimentary structures that typically do not employ construction techniques capable of ensuring their safety and stability.

Table 1 - Classification of the Reservoirs in the Sertões de Crateús Basin

Classification	Storage Capacity	Number
Small Reservoirs	300.000 m <sup>3</sup> - 3.000.000 m <sup>3</sup>	42
Medium Reservoirs	3.000.000 m <sup>3</sup> - 10.000.000 m <sup>3</sup>	8
Large Reservoirs	maiores que 10.000.000 m <sup>3</sup>	5
Barreiros	< 300.000 m <sup>3</sup>	227

Source: Authors (2026).

### 3.4 Validação dos Métodos

The primary information regarding the heights and volumes of the known dams can be found on the Hydrological Portal of Ceará, an online platform frequently updated by COGERH, which contains the technical data sheets for all dams monitored by the agency.

Table 3 presents the 9 monitored earth dams in the BSC with known data, alongside the single dam whose data was verified through a field survey, totaling 10 dams used to validate the methodology.

*Table 3 - Reservoirs Used for Method Validation*

<b>Reservoir</b>	<b>Municipality</b>	<b>Data Source</b>
São José III	Ipaporanga	Ceará Hydrological Portal
Sucesso	Tamboril	Ceará Hydrological Portal
Carnaubal	Crateús	Ceará Hydrological Portal
Realejo	Crateús	Ceará Hydrological Portal
Jaburu II	Independência	Ceará Hydrological Portal
Cupim	Independência	Ceará Hydrological Portal
Barra Velha	Independência	Ceará Hydrological Portal
Flor do Campo	Novo Oriente	Ceará Hydrological Portal
Colina	Quiterianópolis	Ceará Hydrological Portal
São Francisco	Crateús	Field Survey

*Source: Authors (2026).*

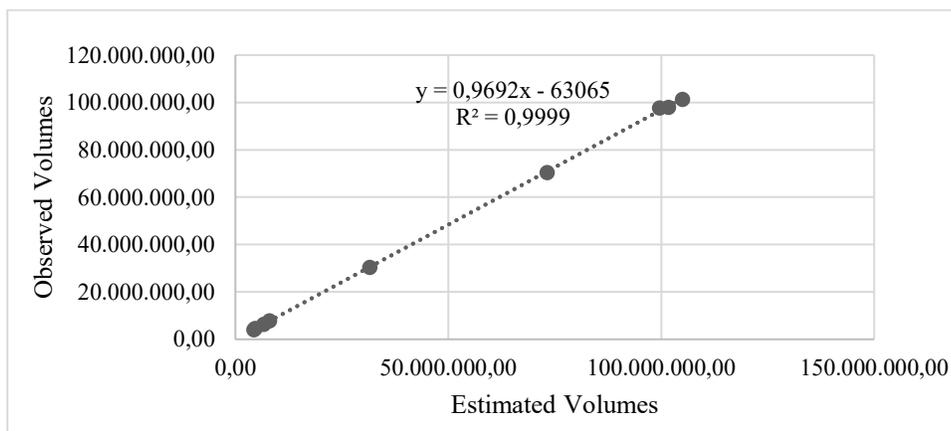
All the reservoirs used for data validation (Table 4) had their actual volumes and heights compared to those estimated by this study. Tables 3 and 4 present the variation values from this comparison, as well as the relative percentage error of the estimation. For this sample, the comparative analysis based on the established criteria reveals a coefficient of determination between the actual and estimated volumes and heights that follows a trendline. It can be observed that the coefficients of determination obtained are close to 1 (one) for all scenarios, indicating a strong correlation between the actual and estimated data, as illustrated in Graphs 3 and 4.

*Table 4 – Results Obtained from the Comparison Between Observed and Estimated Volumes*

Reservoir	Volume			Relative Error
	Observed	Estimated	Variation	
São José III	7.960.000,00 m <sup>3</sup>	7.797.811,27 m <sup>3</sup>	162.188,73 m <sup>3</sup>	2,0%
Sucesso	6.600.000,00 m <sup>3</sup>	6.278.832,01 m <sup>3</sup>	321.167,99 m <sup>3</sup>	4,9%
Carnaubal	73.200.000,00 m <sup>3</sup>	70.464.736,64 m <sup>3</sup>	2.735.263,36 m <sup>3</sup>	3,7%
Realejo	31.550.000,00 m <sup>3</sup>	30.425.942,73 m <sup>3</sup>	1.124.057,27 m <sup>3</sup>	3,6%
Jaburu II	101.641.000,00 m <sup>3</sup>	97.945.254,16 m <sup>3</sup>	3.695.745,84 m <sup>3</sup>	3,6%
Cupim	4.600.000,00 m <sup>3</sup>	4.528.779,76 m <sup>3</sup>	71.220,24 m <sup>3</sup>	1,5%
Barra Velha	99.560.000,00 m <sup>3</sup>	97.640.641,66 m <sup>3</sup>	1.919.358,34 m <sup>3</sup>	1,9%
Flor do Campo	105.000.000,00 m <sup>3</sup>	101.343.491,18 m <sup>3</sup>	3.656.508,82 m <sup>3</sup>	3,5%
Colina	4.290.000,00 m <sup>3</sup>	4.021.679,46 m <sup>3</sup>	268.320,54 m <sup>3</sup>	6,3%
São Francisco	Unavailable	8.998.830,98 m <sup>3</sup>	-	-

Fonte: Autores (2026).

Graph 3 - Results of the Comparison Between Observed and Estimated Volumes



Source: Authors (2026).

It is important to highlight that the São Francisco Reservoir, located in the municipality of Crateús, was the only reservoir in the validation set whose actual dam height was measured in the field. The height of the São Francisco dam exhibited a difference of 1.55 m, representing the most discrepant value among the reservoirs used for validation. Consequently, it yielded the highest relative percentage error, at approximately 14%. This outcome may be attributed to the fact that the downstream embankment of this dam presents varying inclinations along its length. The mean slope

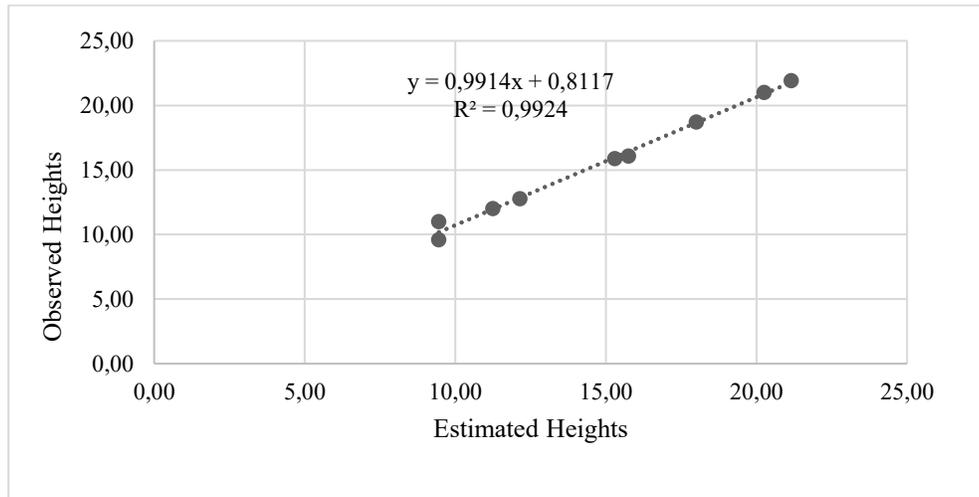
measured in the field was 65%, resulting in an average dam height of 11 meters. These comparative results between the observed and estimated heights are detailed in Table 5 below.

*Table 5 – Results Obtained from the Comparison Between Observed and Estimated Heights*

Reservoir	Height			Relative Error
	Observed	Estimated	Variation	
São José III	Indisponível	9,00 m	-	-
Sucesso	12,77 m	12,15 m	0,62 m	4,9%
Carnaubal	18,70 m	18,00 m	0,70 m	3,7%
Realejo	21,00 m	20,25 m	0,75 m	3,6%
Jaburu II	15,88 m	15,30 m	0,58 m	3,7%
Cupim	9,60 m	9,45 m	0,15 m	1,6%
Barra Velha	16,06 m	15,75 m	0,31 m	1,9%
Flor do Campo	21,91 m	21,15 m	0,76 m	3,5%
Colina	12,00 m	11,25 m	0,75 m	6,3%
São Francisco	11,00 m	9,45 m	1,55 m	14,0%

*Source: Authors (2026).*

*Graph 4 - Results of the Comparison Between Observed and Estimated Volumes*



Source: Authors (2026).

### 3.5 Classification under law 14.066/2020

In this stage, complying with the criteria required by current legislation and considering that the analyzed reservoirs do not store hazardous waste, all Medium and Large Reservoirs were classified based on the height and volume requirements. For Small Reservoirs, drawing on the examples from studies by Anderáos (2013) for a fictitious dam, the classification into Risk Category (CRI) and Associated Potential Damage (DPA) was verified. Consequently, the Associated Potential Damage (DPA) category was also assessed for the *Barreiros* (Small Earth Dams) in the sample. It is important to emphasize that the scores assigned in Tables 2 and 3 refer to the Small Reservoirs and *Barreiros*, aiming to verify whether they meet the requirements for a medium or high DPA classification, given that the legal thresholds related to dam volume and height were insufficient to classify them. A score was assigned based on Technical Characteristics (CT), Safety Plan (PS), and State of Conservation (EC), as suggested by the CNRH (2012) classification and the study conducted by Anderáos (2013).

Given the inability to conduct on-site verifications of the Technical Characteristics (CT), the estimated height data from this study and the Ruler tool in Google Earth were used to measure the dam lengths. Lengths under 200 meters (receiving 2 points) and over 200 meters (receiving 3 points) were identified for the dams of Small Reservoirs. These dams have unknown ages and design flow rates; therefore, 4 and 10 points were assigned, respectively. Regarding the score for the Safety Plan (PS), since this analysis deals with unmonitored reservoirs lacking information from Public Authorities, the assigned scoring is illustrated in Table 6. For the State of Conservation (EC), Google Earth imagery was used to check for the possible presence of spillways and whether the dam slopes showed signs of vegetation growth.

The verification of the DPA for Small Reservoirs and *Barreiros* (Table 7)—one of the criteria for classifying reservoirs under Law No. 14.066/2020—was based on the scores assigned regarding the estimated reservoir capacity in this study, the potential loss of human life, environmental impact, and socioeconomic impact. A detailed description of the conditions used for the DPA classification is presented in Table 4, mentioned earlier in this work.

Table 6 - Risk Category (CRI) for the Small Reservoirs in the Sample

Technical Characteristics (CT)								
Analyzed Types	Heights (m)	Lengths (m)		Material	Foundation	Age	Design Discharge	Total
Small reservoirs	< 15	< 200	>200	Homogeneous Earth	Soft Rock / Compacted Soil Foundation	Unknown	Unknown	
UNITS	0	2 - 3		3	4	4	10	24
Safety Plan (PS)				Conservation Status (EC)				
Analyzed Types	Project Documentation	Safety Team	Monitoring and Inspection	Reports	Structural Reliability	Seepage / Spillways	Slope Deterioration	Total
Small reservoirs	Nonexistent	No Technical Responsibility	No Technical Responsibility	Not Issued	No Information	Moisture / No Spillways	Vegetation Growth	
UNITS	8	8	6	5	-	4	5	36

CRI = CT + OS + EC = 60 (Classified as HIGH)

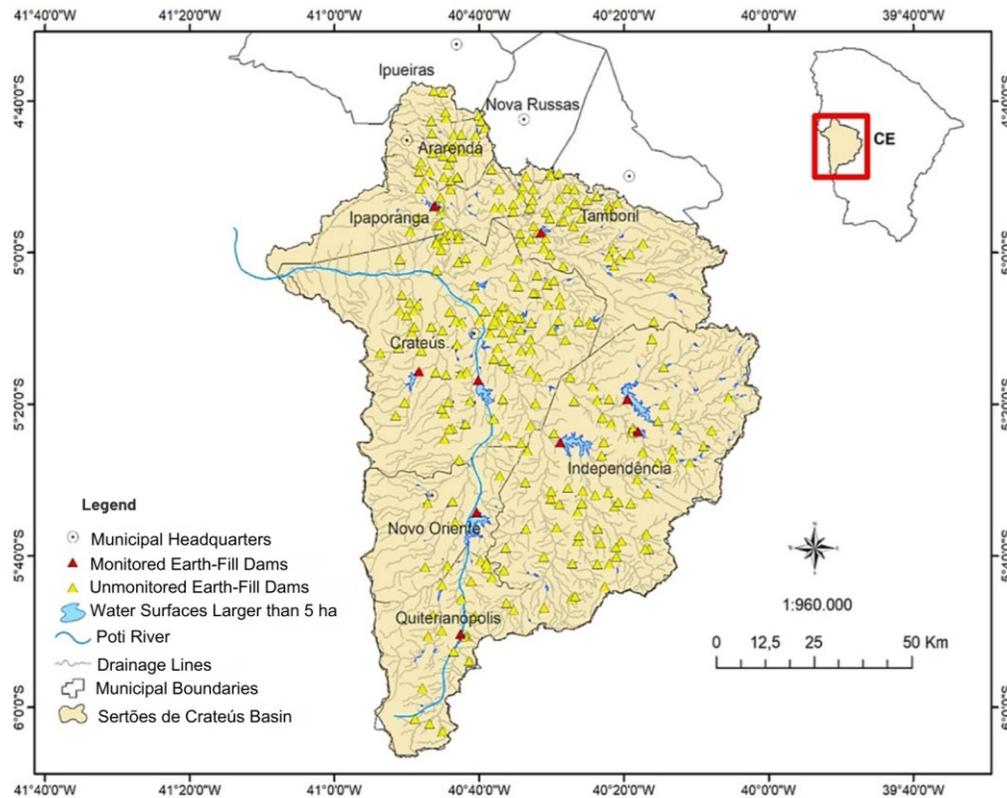
Source: Authors (2026).

Table 7 - Associated Potential Damage (APD) for the Small Reservoirs and Barreiros in the Sample

Associated Potential Damage (DPA)						
Analyzed Types	Capacity (m <sup>3</sup> )	Potential Loss of Human Lives	Environmental Impact	Socioeconomic Impact	Total	Classification
Barreiros	< 300.000	Infrequent	Significant	Nonexistent	8	DPA < 10
UNITS	1	4	3	0		LOW
Small Reservoirs	Between 300.000 and 3.000.000	Frequent	Significant	Low	16	DPA > 16
UNITS	1	8	3	4		HIGH

Source: Authors (2026).

The DPA criterion ensures that Small Reservoirs are also subject to the legislation. However, the *Barreiros* in the sample are not included in this classification, as they do not meet any of the pre-established criteria outlined in the law. Consequently, a total of 55 potential earth dams fall within the scope of Law No. 14.066/2020, encompassing a variety of small, medium, and large reservoirs, 9 of which are monitored by Public Authorities (Figure 8).



*Figure 8 - Location of Dams Classified Under Law No. 12.334/2010*  
Source: Authors (2026).

For all 55 dams that fall under the legislation according to this study, their locations were mapped and categorized by municipality. Furthermore, summary tables were compiled detailing the primary characteristics of all these structures, namely: perimeter and surface area, geographic coordinates, estimated volumes and heights, and reservoir classification based on Molle (1994b). Consequently, it is possible to visualize the dams located within the territory of each contributing municipality of the basin on the maps (Figures 15 to 23) and cross-reference them with their respective characteristics in the summary tables (Tables 9 to 17).

#### 4. Conclusions

This work presented a study aimed at identifying potential earth dams in the Sertões de Crateús Basin and determining their characteristics. Based on the mapping of water bodies in Ceará conducted by FUNCEME and satellite imagery obtained from Google Earth, it was possible to identify 390 water surfaces larger than 5 hectares across the basin. The identified water bodies were categorized according to the type of material used in the dams. These 390 water surfaces are divided into: 21 natural reservoirs, 1 reservoir with a concrete dam (Batalhão Reservoir), and 86 water bodies with the appearance of artificial lakes. This categorization yielded 282 potential artificial reservoirs with earth dams distributed among the contributing municipalities of the basin.

The study was restricted to earth dams, as they represent the most widespread water solutions in the region and are suitable for the application of simplifying methodologies, such as the one adopted in this work. Through the use of GIS tools and the simplifying methodology suggested by Araújo *et al.* (2012), it was practically feasible to obtain the reservoir volumes and the heights of the 282 earth dams identified in the study. Based on the classification proposed by Molle (1994), a generalized overview of the capacity of these 282 reservoirs was obtained, along with the identification of the most widespread water impoundment technique utilized by the developers of these structures. The classification revealed that the basin consists mostly of Small Earth Dams / *barreiros* (80.5%) and Small Reservoirs (14.9%). Medium and Large Reservoirs represent only 2.8% and 1.8%, respectively, of the total earth dams identified in this study.

In light of this classification, understanding the composition of the basin reinforces the notion that the construction of small dams is the primary technique applied by private landowners in an attempt to ensure water storage for periods of scarcity. Results were obtained with an accuracy between 94% and 98%, and a coefficient of determination close to 1 (one), specifically 0.999 for volumes and 0.992 for dam heights. Therefore, it can be stated that the method performed well for the reservoirs in this basin. The classification of the dams carried out according to the criteria of Law No. 14.066/2020 demonstrated that a considerable number of structures fall under the legislation—at least 55 dams identified in this study (19.5% of the basin's earth dams) require greater attention from their legal guardians. This information raises a red flag, given that these are reservoirs unknown to public authorities, and some have even ruptured recently.

For the safety of the region's dams and their compliance with the proposed legislation, it is recommended that the remaining 46 dams, which currently lack any form of oversight, be monitored by their respective owners to ensure population safety, environmental preservation, and operational viability, among other factors. Thus, the proposed objectives of this work were successfully achieved. For future work, a finer refinement of the sample is suggested using satellite imagery more precise than that provided by Google Earth, to eliminate any doubts regarding the existence of dams in the region. It is also recommended to observe how this study would perform in other basins by applying the same procedures detailed here. Finally, the obtained results could be used for a case study of the 55 identified dams, focusing on, for example, the identification of their owners, their current uses, and their present condition, among other possible analyses.

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