



## Estimates of volume and sedimentation of the reservoir of the Itacarambi River dam, Minas Gerais, Brazil

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**ABSTRACT:** The dam of the Itacarambi River, located in São João das Missões, MG, Brazil, is a hydraulic containment created by CODEVASF in 1988 to regulate the flow and perpetuation of the river, water storage for human and animal supply, irrigation and fish farming. At the beginning of its operation, the reservoir had a volumetric capacity of 7,388 hm<sup>3</sup> in an area of 100 ha. The aim of this study was to conduct a bathymetric survey for production of a bathymetric chart and calculation of morphometric parameters. The data collected showed that the Itacarambi river reservoir dam had constant irregularities in its bottom, forming submerged sandbanks, which may be a reflection of silting over the years. A volume of 5.75 hm<sup>3</sup>, that is, 20% of its original capacity, was predicted to be lost in the area occupied by the dam (100 ha). The estimated sedimentation rate was 62,347.8 m<sup>3</sup> year<sup>-1</sup> and the lifetime of the reservoir was 115 years since the beginning of operation.

**Keywords:** dam, bathymetric survey, morphometric characteristics.

### Estimativas do volume e assoreamento do reservatório da barragem do Rio Itacarambi, Minas Gerais

**RESUMO:** A barragem do rio Itacarambi, situada em São João das Missões, MG, é uma contenção hidráulica criada pela CODEVASF em 1988 para regularização da vazão e perenização do rio Itacarambi, armazenamento de água, abastecimento humano e animal, irrigação e piscicultura. No início do seu funcionamento o reservatório da barragem possuía 7,388 hm<sup>3</sup> de capacidade volumétrica em área de 100 ha. O objetivo deste trabalho foi realizar um levantamento batimétrico que possibilitou a confecção de carta batimétrica e cálculo de parâmetros morfométricos. A partir dos dados levantados, o reservatório da barragem do rio Itacarambi apresentou constantes irregularidades no seu fundo, com formação de bancos de areia submersos, que podem ser reflexo do assoreamento ao longo dos anos. Na área ocupada pela barragem (100 ha) foi predito um volume equivalente a 5,75 hm<sup>3</sup>, isto é, redução de 20% da sua capacidade original. A taxa de sedimentação estimada foi de 62.347,8 m<sup>3</sup> ano<sup>-1</sup> e o tempo de vida útil do reservatório de 115 anos desde o início de funcionamento.

**Palavras-chave:** barragem, levantamento batimétrico, características morfométricas.

## 1. INTRODUCTION

In arid and semi-arid regions, which are subjected to water shortages, it is necessary to know the hydrosedimentological processes in order to ensure the permanence and survival of man in the field (SANTOS; SRINIVASAN, 2012), as for example, the water supply to cities.

In this sense, the Cerrado of northern Minas Gerais is a biome whose rainfall rate is unevenly distributed throughout the year. Precipitations is concentrated in the months of spring and summer (october to march). Frequency and intensity of rainfall falls from May to September, resulting in a season with little or total absence of rain (MARCUIZZO et al., 2012).

In the north of Minas Gerais, water supply systems that rely solely on direct uptake from watercourses would not have the

capacity to meet the demand of the region during the dry season, especially if the period of drought is severe.

Many rivers, in the dry season of the year, have little or no water flow, and after heavy rains they have intense currents (CABRAL, 2005). Thus, construction of dams has the aim to regularize the flow of the course and hence the frequent supply to users. For this reason, the Itacarambi River dam was created. This is located in the north of Minas Gerais, near the municipality of São João das Missões. The water dammed by the Itacarambi River dam supplies users living in the municipalities of São João das Missões, Manga, Itacarambi, and other nearby districts, and serves for irrigation of local crops.

However, any reservoir, regardless of its purpose and operating characteristics, is subject to silting process. Due to the reduction of water flow and the enlargement of the cross section,

reservoirs are eventually subjected to conditions that favor the sedimentation of solid materials carried by the watercourse or arising by runoff from the basin (ALBERTIN et al., 2010). The lack of vegetation in the basin intensifies the silting process. A single event of rainfall may cause soil particles to detach and be carried by runoff and deposited in the lower parts of the topography or in the bed of the water course, silting it. Increased sedimentation leads to decreased volumetric capacity of the reservoir and consequent reduction of its efficiency. According to Leda et al. (2014) the presence of vegetation helps to maintain ecosystem services in the basin.

Besides reducing the capacity of the reservoir, Albertin et al. (2010) call attention to operational problems related to sedimentation, such as abrasion components; pipes, turbine blades; mechanical problems to the gates; reduction in water capture efficiency; drowning of spawning, feeding and shelter space for fish; formation of sandbars that decrease the draft for navigation, and above all, the safety of the dam.

The water volume and siltation within the reservoir can be estimated by means of bathymetric maps. They aid to monitor the siltation rate and to manage the basin in order to prevent sedimentation to increase. In Brazil, the monitoring of sedimentation in reservoirs must be done through bathymetric surveys carried out by echo sounders, in accordance with the guidelines of the National Water Agency - ANA (2013). According to Rotta et al. (2012), bathymetry can be carried out through the emission of sound waves by the echo sounder that, when passing through the water column, propagate efficiently. This is the best alternative to obtain information about a submerged desired target. Bathymetry gives information on the depth of the reservoir. The greater the number of points, the more reliable is the interpolation of areas with no information available. It is possible to see through these points the elevation of the bottom of the water column at various georeferenced points, and then, by interpolation, the shape of the reservoir bottom.

Reservoirs have some basic morphological and morphometric conditions that change with time depending on a number of factors. These include hydrological events that typically occur basins, but also, and especially, events caused by human activity (CIGAGNA et al., 2014).

The morphology of reservoirs means the study of its form while morphometry deals with the quantification of these forms and elements (TUNDISI; MATSUMURA-TUNDISI, 2008). The characterization of morphometric parameters of lakes and reservoirs are important for studies that aim to record the evolution of silting, preserve and restore the ecological quality, and control eutrophication processes. (CIGAGNA et al., 2014).

The objective of the present study was to establish the morphometric parameters of the Itacarambi river dam reservoir, as well as predict the quantification of the volume of dammed water, the silted volume, and estimate the lifetime of the Itacarambi river dam reservoir in the north of Minas Gerais.

## 2. MATERIAL AND METHODS

The study was initiated in June 2011 in the Itacarambi River dam, a tributary of the São Francisco River basin (Figure 1). The dam is located in the city of São João das Missões between the towns of Manga and Itacarambi in the northern of Minas Gerais. The geographical coordinates and altitude are 14°48'7,57" S and

44°16'25,94" W, and 480 m, respectively. According to Köppen-Geiger classification, the region has Aw climate (tropical with dry season), the average annual temperature is around 24.4°C and the average annual rainfall is 855 mm.

The dam (Figure 1) was built by the Company of Development of São Francisco and Paraíba Valleys (CODEVASF) in 1980-1988. The dam was built with the purpose to regulate the flow and perpetuate the river, to store water for human and animal supply, for irrigation and for fish farming. The area of the river basin is 38,100 ha, and the drainage area is around 1,000 ha. Since its construction, no bathymetric survey has been carried out. In its project, the dam reservoir covered an area of 100 ha, with total capacity of 7,388 hm<sup>3</sup> and useful volume (between the minimum and maximum operating levels) of 7,225 hm<sup>3</sup>. Its maximum operating level is 485.5 m, and the minimum is 470.5 m.

The study methodology was adapted from Resck (2007). Collection of bathymetric data from the Itacarambi river dam reservoir was made with an echo sounder device (SonarLite Ohmex Ltd) coupled to a GPS (DGPS AgGPS 132 -Trimble Co) in a vessel. The echo sounder transducer and the GPS antenna were fixed at the end of the vessel. The movement of the vessel followed approximate perpendicular lines throughout the dam thalweg and lines that were parallel to the dam, starting from the containment with an average speed of 5 km h<sup>-1</sup>. The water level in the day of collecting data was 485.0 m, half a meter below the sangria quota.

Data collected in the survey through surface of the water reservoir (navigable circumference) were processed, arranged in positions X, Y and Z (horizontal and vertical distance and depth) in the *Microsoft Excel* software saved in .xls format and then imported into the software *Surfer 13<sup>®</sup> (Demo Version)* (Golden Software Inc.) and saved in grd format. In this program, the bathymetric map was generated using Kriging as the interpolation method as according to Pereira et al. (2012); Ferreira et al. (2012), the Kriging method is the best for representing for interpolating the riverbed depth profile with real fidelity using the software *Surfer* and bathymetry presents ideal characteristics for using this interpolator.

The reservoir volume was estimated at *Surfer*; both, the total volume and the volumes for each level of depth. The water level, called Level 0, represented the total volume and its magnitude was reduced with the depth every one meter, estimated like this, 1 to 1 m, that is, for each level of depth, the total volume referent to that level was calculated.

In areas located at the ends of the reservoir that were non-navigable due to dense aquatic vegetation, preventing the access of the vessel, it was not possible to make the collection of data with the echo sounder. Area and volume of these points were manually defined without the vessel with GPS and millimetric ruler.

In the data of area and volume for each level of depth, the hypsographic curves depth-area and the depth-volume, both in percentage, were generated. Values of depth were plotted in negative order and percentages of area and volume were plotted on the graph in the positive abscissae.

On the day of collection, the water level was below the level corresponding to full capacity of operation. It is expected, therefore, that the area of contribution of the reservoir when flooded be less than 100 ha, which is the area defined in the project designed in 1988. In the sequence, the data on depth-area

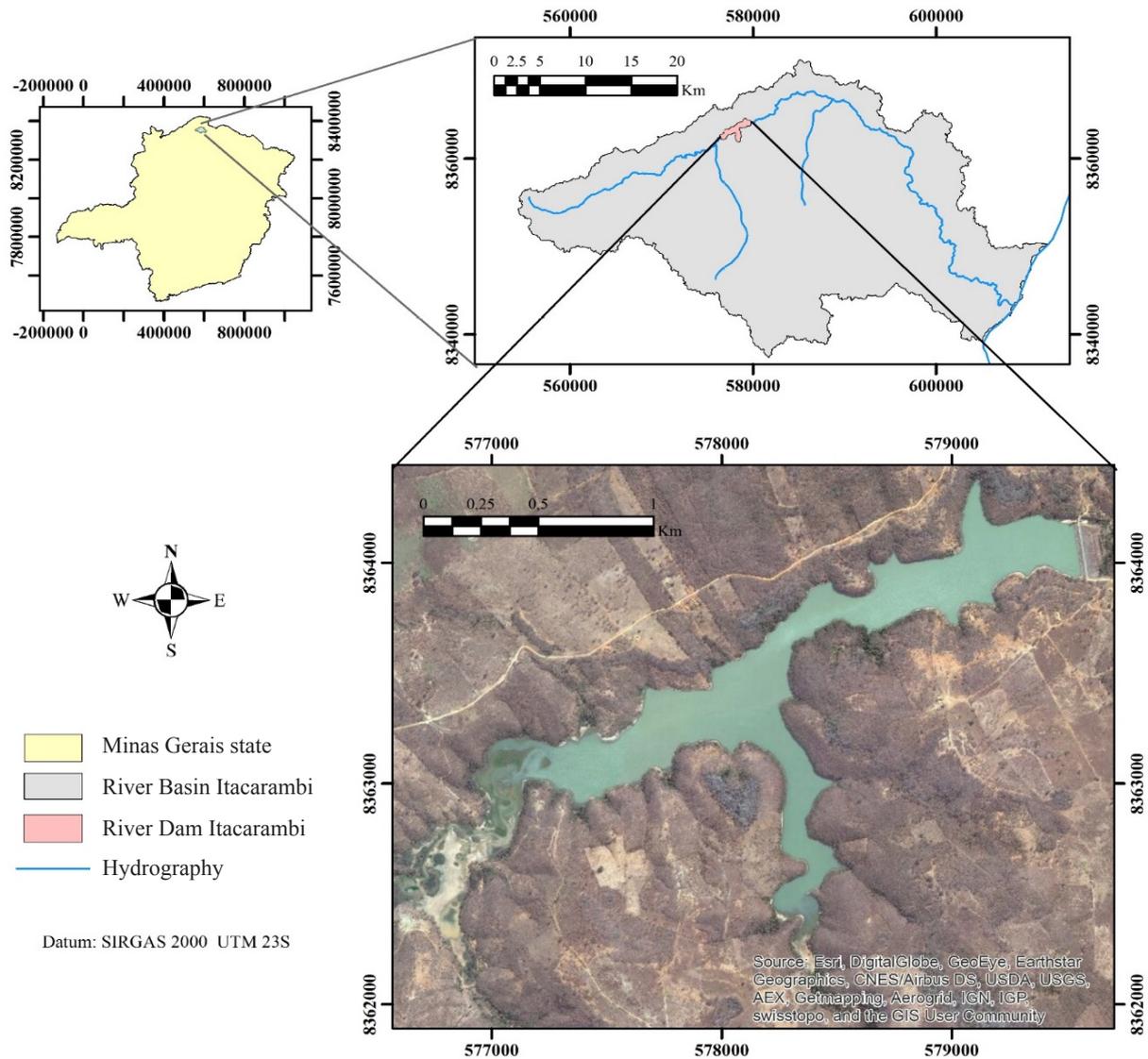


Figure 1. Location of the Itacarambi River Basin, and of the Itacarambi river dam.  
 Figura 1. Localização da Bacia do rio Itacarambi, e da barragem do rio Itacarambi.

and depth-volume were the basis for a polynomial function to estimate the volume equivalent to an area of 100 ha, for later comparison of the capacity between 1988 and 2011.

Primary and secondary morphometric parameters were also defined according to the same methodology used by Resck (2007). Primary parameters, namely, area, perimeter, maximum depth, diameter, volume and length, were directly obtained. Secondary parameters, in turn, were obtained through the establishment of relationships between primary parameters. These were relative depth, mean depth, development index, mean width and mean slope. According to von Sperling (1997), relative depth can be determined dividing the value of maximum depth of the lake by the mean diameter. The diameter corresponds to the diameter of a circle that encloses the area of the reservoir, and this parameter is expressed in percentage (Eq. 1).

$$Z_r = \frac{Z_{max}}{\text{mean diameter}} \times 100 \quad (1)$$

where:

$Z_r$  - relative depth, %;

$Z_{max}$  - maximum depth, m.

Mean depth was determined by the ratio between the accumulated volume of water and the area of the water mirror (Eq. 2).

$$Z = \frac{V}{A} \quad (2)$$

where:

$Z$  - mean depth, m;

$V$  - accumulated volume,  $m^3$ ;

$A$  - area of the water mirror,  $m^2$ .

The index of perimeter development is an index that is estimated by the ratio between the perimeter of the lake and the circumference of a circle with the same area of the lake (Eq. 3).

$$D_p = 0.28 \frac{P}{\sqrt{A}} \quad (3)$$

where:

$D_p$  - perimeter development index;

$P$  - perimeter, m;

A - area of the water mirror, m<sup>2</sup>.

The average width of the lake (L<sub>med</sub>) was calculated by the ratio between the area and the maximum length (Eq. 4).

$$L_{med} = \frac{A}{C_{max}} \quad (4)$$

where:

l<sub>med</sub> - mean width, m;

A = area of the water mirror, m<sup>2</sup>;

C<sub>max</sub> - maximum length, m.

The mean slope ( $\alpha$ ) was calculated by Eq. 5.

$$\alpha = 100 \frac{Z_{max}}{\sqrt{\frac{A}{\pi}}} \quad (5)$$

where:

$\alpha$  - mean slope, %;

Z<sub>max</sub> - maximum depth, m;

A - area of the water mirror, m<sup>2</sup>.

The mean sedimentation rate per year was calculated by subtracting the value of volume of 2011 from the initial volume for construction of the river Itacarambi dam in 1988, and divided by the number of years, that is, 23 years. This same methodology was used by Santos (2009) (Eq. 6).

$$S = \frac{\Delta V}{T} \quad (6)$$

where:

S - volume of sedimentation, m<sup>3</sup> year<sup>-1</sup>;

$\Delta V$  - difference between the volumes, m<sup>3</sup>;

T - sedimentation time, years.

The lifetime of Itacarambi River dam was calculated according to Eq. 7, the same method used by Bufon et al. (2009).

$$T_v = \frac{V \times T}{St} \quad (7)$$

where:

T<sub>v</sub> - lifetime, years;

V - volume of the reservoir, m<sup>3</sup>;

T - time of comparison between one measurement and another, years;

St - sedimentation over time of comparison or  $\Delta V$ , m<sup>3</sup>.

### 3. RESULTS AND DISCUSSION

The bathymetric survey of the Itacarambi river Dam was made with a total of 3,099 points collected with echo sounder, geographical location and known depths (X, Y and Z).

The area of the reservoir was 90.06 h (Figure 2) in the day of collection, 84.35 ha were obtained through bathymetric surveys, collected with echo sounder, with the displacement of the vessel into the reservoir, and the remaining 5.71 ha were obtained

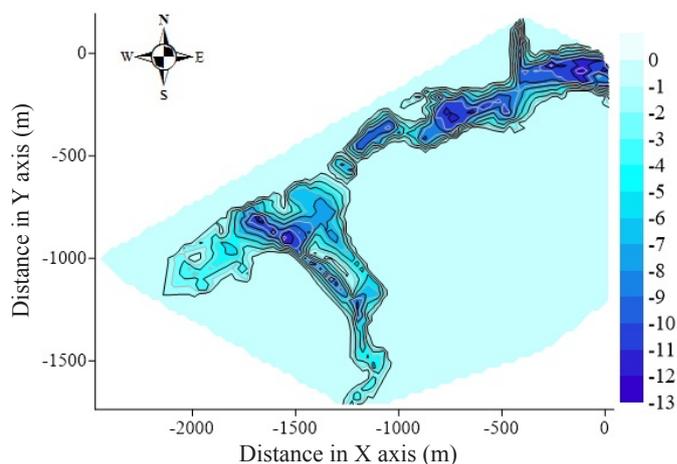


Figure 2. Bathymetric chart of the depth level curve as estimated at every meter.

Figura 2. Carta batimétrica da curva de nível de profundidade de metro em metro.

through manual bathymetric survey using millimetric ruler for data collection. This last area corresponds to non-navigable marginal areas along the entrance of the watercourse in the reservoir. The mean depth was 1.5 m in this location.

The bathymetric map of the dam reservoir is represented with meter level curves at every meter of depth, reaching maximum level of 14 m of depth (Figure 2). The points with dark tones address deeper locations within the reservoir. As expected, deeper levels occur in the central part of the accumulation basin. However, the advancement of the dark color is not continuous, not extending along the thalweg, and this indicates variability in the level of depth, which may be due to sedimentation.

Figure 3 presents in top view the three-dimensional image of the accumulation basin. Increasing depth is also seen with proximity with the edges of the reservoir, the shallow regions, and this is expected due to the flooding process of the area by damming of the course, and not due to the silting process. In other hand, the elevation of the relief in some points within the reservoir indicates the formation of submerged sand banks in the middle of the reservoir, similar to what was observed by Resck, et al. (2007). Sand banks are formed due to silting in the

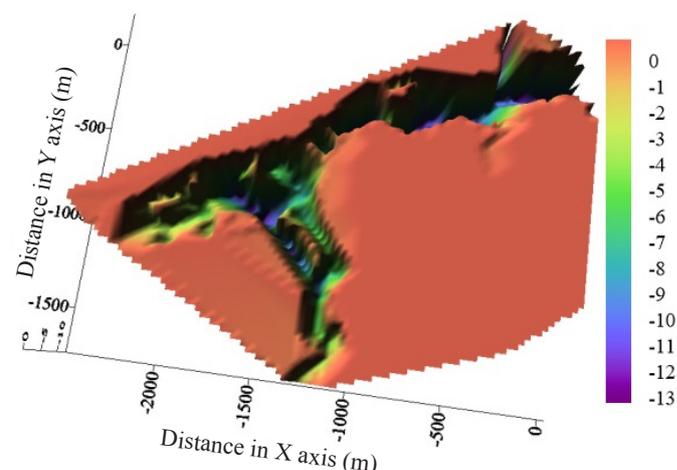


Figure 3. Three-dimensional view of the bathymetric chart of the accumulation basin.

Figura 3. Vista em 3D da carta batimétrica da bacia de acumulação.

case of the Itacarambi river dam, these are present submerged at various points as small clusters. They do not appear in elongated forms. This happens because this is a reservoir whose damming slows the water flow and the sediment decanted undergoes little motion, especially in the flow direction, compared to a water course silted with continuous flow, as occurs .

The longitudinal perspective of the reservoir, following the deepest points along the thalweg (Figure 4), shows constant irregularities in the bottom of the reservoir. It is important to monitor this change over time, as submerged sandbanks are formed and can undergo displacement over time.

The dam is intended to regulate the Itacarambi river, but in the rainy season the flow increases, accelerating the flow and increasing the displacement of sand banks. Fonseca et al. (2011) found in their study a sand bank shift of 1.8m/year in the enseada dos Anjos, Arraial do Cabo, RJ.

Using the Surfer software, the area and volume at each depth level of the reservoir was determined. The level 0 corresponds to the water level, and associated to this level is the total volume and area of the reservoir (Table 1).

Based on this data, depth-area hypsographic curves and, in the same graph, depth-volume curve (Figure 5) were generated. Volume and area were plotted in percentage for each depth level. These curves show the frequency of occurrence of the water volume in relation to the water mirror area in different water depths. These relationships become essential to the morphometric knowledge of water bodies. The shape of the lake cavity can be evidenced by analyzing the hypsographic curves (BEZERRA-NETO; PINTO-COELHO 2002). According to Resck, et al. (2007), it is important to know the depth-area hypsographic curves and depth-volume curves for better

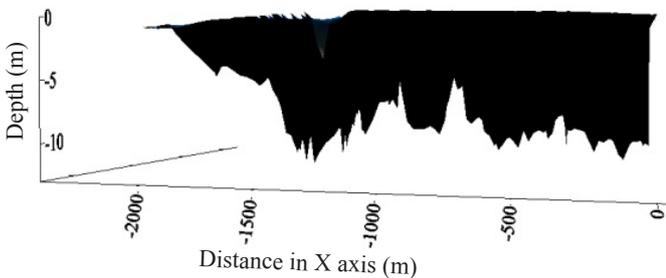


Figure 4. Longitudinal perspective along the thalweg of the reservoir.

Figura 4. Corte da perspectiva longitudinal em sentido do talvegue do reservatório.

Table 1. Volume and area for each depth level of the reservoir.  
Tabela 1. Volume e Área referentes a cada cota de profundidade do reservatório

Level (m)	Volume (hm <sup>3</sup> )	Area (ha)
0.0	4.65	90.06
-1.0	3.40	74.39
-2.0	2.59	61.88
-3.0	1.91	51.00
-4.0	1.44	42.64
-5.0	1.05	35.64
-6.0	0.73	29.04
-7.0	0.47	22.24
-8.0	0.28	16.56
-9.0	0.14	11.46
-10.0	0.05	6.05
-11.0	0.01	1.71
-12.0	4.10 <sup>-4</sup>	0.14
-13.0	4.6.10 <sup>-6</sup>	4.7.10 <sup>-3</sup>

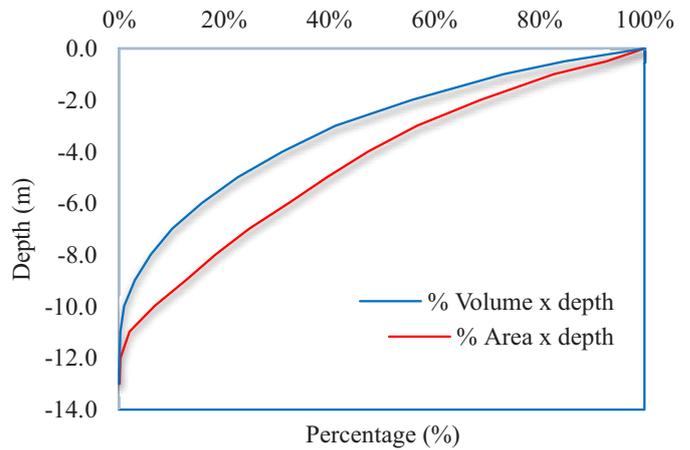


Figure 5. Depth-area hypsographic curve and depth-volume curve.

Figura 5. Curvas hipsográficas profundidade-área e curva profundidade-volume.

planning and managing the reservoir, as well as interventions that may lower the water surface.

The reservoir area, after bathymetric surveys, was 90.06 ha and its volume was 4.65 hm<sup>3</sup> (Table 1). In order to set the volume corresponding to the area of 100 ha, the polynomial function displayed in the Figure 6 using the data presented in Table 1 was generated. With this polynomial function, the volume corresponding to an area of 100 ha, area of the reservoir according to the 1988 project, was estimated. This volume was of approximately 5.75 hm<sup>3</sup>.

In the year of construction, the volumetric capacity of the reservoir was 7,388 hm<sup>3</sup>. In 23 years, a reduction of 1,434 hm<sup>3</sup> has taken place. A study carried out by the World Bank showed that the annual loss of reservoirs, that is, the volume of water that becomes silted, is 1%, showing variations from locations and countries. In Brazil, this percentage is 0.5% due to population growth and consequent erosions. The same study showed that the reservoirs of all countries of the world have had their lifetime shortened from 100 to 22 years (MAHMOOD, 1987). According to the National Electric Energy Agency - ANEEL (2000), the lifetime of a reservoir, regardless of its purpose, is when the silting reaches the threshold of the power intake, which is the base of the spillway. Brazil already has many fully or

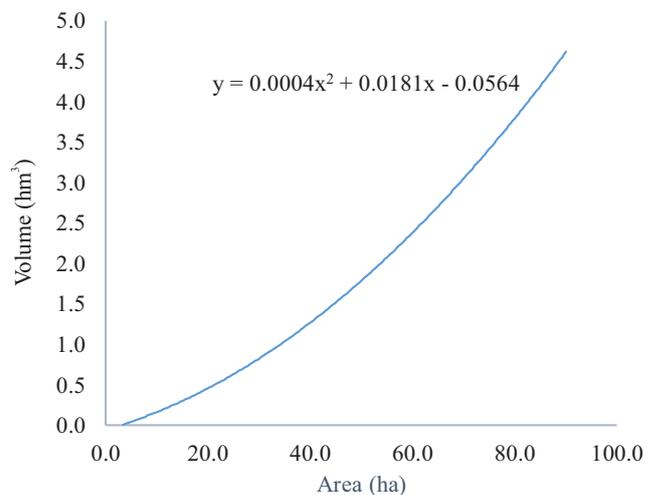


Figure 6. Frequency of volume occurrence according to area.  
Figura 6. Frequência de ocorrência do volume em função da área.

partially silted reservoirs and many that, due to lack of systemic morphometric surveys, do not have their situation known.

As no other bathymetric survey has been carried out to aid the evolution of silting in the river dam reservoir, it is assumed that the loss of volume is due to the sedimentation process over the 23 years. Whereas this silting has occurred in ascending order, the Itacarambi river dam reservoir tends to be silted in  $62,347.8 \text{ m}^3 \text{ year}^{-1}$ , leading to 115 years of useful life, with initial mark at the start of operation in 1988.

The reservoir capacity has been reduced by 20%, approximately 0.86% per year above the estimated percentage to Brazil (MAHMOOD, 1987). Albertin et al. (2010) found a 14% reduction of reservoir capacity in 36 years. According to this author, from the moment that the accumulated sediments meet the threshold of the water intake, there are no more conditions for the proper operation of the reservoir, meaning that this is the end of its useful life.

Table 2 shows morphometric parameters of the water reservoir of the Itacarambi river dam.

The relative depth ( $Z_r$ ) represents a good parameter to describe the flow pattern of a water body (von SPERLING, 1999). In the largest lakes, lower  $Z_r$  than 2%, only in deep lakes and when they have small surface areas, they present generally higher relative depth than 4% (WETZEL, 2001). The  $Z_r$  of the Itacarambi river dam reservoir was equivalent to 1.31% (Table 2) close to 1. The lagoa do Nado in Belo Horizonte, Minas Gerais, presented relative depth of 2.7 (BEZERRA-NETO; PINTO-COELHO, 2002), being characterized as low-relative depth. According to von Sperling (1997), the high relative depth has low potential for complete mixture of the water column, with negative effect on the oxygenation of the liquid mass. This author says that most of the small and deep lakes have high relative depth, but in large and shallow lakes, this parameter is small. The  $Z_r$  indicates the stability of the water column. When its value is high (5.5%), this suggests a high thermal stability (BEZERRA-NETO; PINTO-COELHO, 2002). Some small reservoirs studied by von Sperling (1997) showed the following relative depths: Serra Branca, MG (5.64%), Pereira Passos, RJ (3.21%), Limoeiro, SP (1.51%).

The perimeter of development ( $D_p$ ) of the Itacarambi river dam was 3.822, considered a high value. The higher the perimeter of development ( $D_p$ ), the greater the importance of marginal vegetation in the ecosystem (WETZEL, 1993). According to Bezerra-Neto; Pinto-Coelho (2002), irregular (or dendritic) bodies of water have  $D_p$  values above 3.0, such as the Itacarambi river dam. Water bodies with  $D_p$  larger than 1, showing irregular shape, tend to be more resistant to external impacts. When the shape is round,  $D_p$  is close to 1, and it is

Table 2. Morphometric characterization sets of the containment Basin of the Itacarambi river dam.

Tabela 2. Conjuntos morfométricos de caracterização da Bacia de contenção da barragem do rio Itacarambi.

Morphometric parameters	
Total volume (V)	4.65 hm <sup>3</sup>
Total area (A)	90.06 ha
Perimeter (P)	12.95 km
Length (L)	3.325 km
Maximum depth ( $Z_{\text{máx}}$ )	14 m
Mean width ( $L_{\text{med}}$ )	270.85 m
Perimeter Development Index ( $D_p$ )	3.822
Relative depth ( $Z_r$ )	1.31%
Mean declivity ( $\alpha$ )	4.63%

therefore the lowest value that can be obtained for  $D_p$ , and the lower this value, the greater is the tendency to silting process (CIGAGNA et al., 2014; BEZERRA-NETO; PINTO-COELHO, 2002). However, any change in the contour of the edge causes the  $D_p$  to exceed the unit (von Sperling, 1999), which agrees with the result because, the Itacarambi river dam is clearly quite irregular. This is different from what happens in the reservoir of the State Forest "Edmundo Navarro de Andrade" - FEENA in Rio Claro, São Paulo, with  $D_p$  1.12 (CIGAGNA et al, 2014.); in the Lagoa Central, Lagoa Santa, Minas Gerais, with  $D_p$  1.38 (BRIGHENTI et al, 2011.); in the lago Parque Norte, Colômbia,  $D_p$  1.31 (RAMIREZ, 2000); the Lagoa Carioca located in the Parque Estadual do Rio Doce - EPRD, Timóteo, Minas Gerais, with  $D_p$  1.29 (TUNDISI; MUSSARA, 1986).

The mean slope of the Itacarambi river dam reservoir was 4.63%. Bezerra-Neto; Pinto-Coelho (2002) obtained a slope of 2.7% to the lagoa do Nado in Belo Horizonte, Minas Gerais. They point that the process of erosion, transport and accumulation of sediments from the basin drainage is intense in that slope, just as it happens in the Itacarambi river dam reservoir.

Human actions are responsible for soil loss process. Among these activities, Santos; Srinivasan (2012) list: the population density combined with the need for increased food production, deforestation of native vegetation, irrigated agriculture and the extensive and intensive livestock. All of these activities have occurred within the Itacarambi river basin and the river has become the target of gathering of sediment production from soil loss, that may be decanted in the Itacarambi river dam, compromising its potential.

Figure 7 corresponds to the partial aerial view of the reservoir and the Itacarambi river dam. In this figure, riparian forest sites still with native vegetation are observed, as well as others spots with little or completely absent vegetation, which favors the soil erosion process.

Increased erosion in the dam can also worsen the management of upstream river basins (LOCHER; SCALON, 2012). Thus, the sedimentological study is necessary for the contribution basin to the upstream damming. According to ANEEL (2000), the rate of increase of sediment transport in the watercourse and in the basin should be included in the evaluation of silting and the lifetime of the reservoir.



Figure 7. Aerial photograph of the reservoir and the Itacarambi river dam. Source: Author

Figura 7. Fotografia aérea do reservatório e da barragem do rio Itacarambi. Fonte: Do autor.

#### 4. CONCLUSIONS

It is concluded that the reservoir volume has decreased from 7.388 hm<sup>3</sup> to 5.75 hm<sup>3</sup>, with 20% deficit in its capacity, with a silting range of 62,347.8 m<sup>3</sup> year<sup>-1</sup>, implying a useful lifetime of 115 years. An integrated management work in the basin upstream of the damming is recommended, with practices of soil and water conservation in order to reduce the silting rate in the reservoir.

#### 5. ACKNOWLEDGEMENTS

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