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Estimate and evaluation of reservoir metrics in Serra da Mesa dam (GO) using the Google Earth Engine platform

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ABSTRACT

The goal of this study was to assess the temporal dynamics of an accumulation reservoir in an accessible and accurate way. The study was conducted on the Serra da Mesa Dam (GO) using orbital images. To estimate the flat area of the dam surface, Landsat TM and OLI images for the period 1998 to 2018 were used. The images were processed using the Google Earth Engine platform (GEE) in order to obtain the dam surface area (km²) and relate it to the flow, altimetric height and volume of the reservoir over the years. The dam showed constant variation of water since its inception, with a decreasing trend. The highest values of the reservoir measurement metrics were observed in the years coincident with the largest areas of the dam, and inversely proportional to the years of the appearance of new dams upstream. More than 90% of the altimetric height variation of water could be explained by the flat area of the dam. The processing platform using the GEE is effective to provide extensive temporal analysis using a large volume of data in a short time, with accurate and robust results.

Keywords: accumulation reservoir, dam, time series.

Estimativa e avaliação das métricas do reservatório de Serra da Mesa (GO) utilizando a plataforma Google Earth Engine

RESUMO

Esse trabalho objetiva a avaliação da dinâmica temporal do reservatório de Serra da Mesa (GO) de maneira semi-automática e precisa, utilizando imagens orbitais. Para estimar a área plana da barragem foram utilizadas imagens Landsat TM e OLI para o período de 1998 a 2018. As imagens foram processadas por meio da plataforma Google Earth Engine a fim de obter a área da barragem (km²), vazão, dimensão e volume do reservatório ao longo dos anos. A barragem apresentou variação constante de água desde o seu início, com uma tendência decrescente. Os maiores valores das métricas de medição do reservatório foram observados nos anos coincidentes com os maiores volumes da barragem e os menores volumes foram detectados após a implementação de novas barragens a montante. Mais de 90% da variação da dimensão da água pode ser explicada pela área plana da barragem. A plataforma de processamento que utiliza o GEE é eficaz para fornecer uma análise temporal extensa e com grande volume de dados em pouco tempo, com resultados precisos e robustos.

Palavras-chave: métricas, reservatório, série temporal.

1. INTRODUCTION

Brazil has 8% of the world's drinking water reserves and concentrates 18% of the planet's surface water potential. Several factors related to land use and economic activity may be responsible for the increased demand for water and excessive consumption. Appropriate management practices are therefore necessary to meet the needs of current and future generations (Paz *et al*., 2000). To meet domestic, industrial and agricultural demand, dams are built in order to retain a certain volume of water, changing the hydrograph due to the retention and release of water, in addition to changing biogeochemical activities (Busker *et al*., 2019).

Due to Brazilian water features, reservoirs were created in order to supply people and generate energy (Machado and Baptista, 2016). The damming of waterways is used to produce electricity, and is also important for other uses such as recreation, fishing, flood control and water supply for population (Moretto *et al*., 2012; Paz *et al*. 2000). Understanding the space-time dynamics of the reservoirs is essential to the conservation of water resources, monitoring of ecosystem services and understanding the impacts of climate change on this feature (Duan and Bastiaanssen, 2013; Tong *et al*., 2016). However, monitoring changes in lakes and reservoirs is still a costly practice and rarely practiced, especially in developing regions (Alsdorf *et al*., 2007; Busker *et al*., 2019; Duan and Bastiaanssen, 2013; Gao, 2015; Tong *et al*., 2016).

The quantification of a reservoir can be obtained by quota-curve determined conventionally using bathymetry of the source, measuring rising depths at various points of the flooded area and making the necessary volume integration (Tong *et al*., 2016). There are few reservoirs with continuous monitoring of the bathymetry due to cost, which varies according to the shape and size of the reservoir (Collischonn and Clarke, 2016). When monitored by measuring stations, errors may occur due to the lack of instrument maintenance (Duan and Bastiaanssen, 2013). Another monitoring alternative is to estimate the volume through mathematical models that relate variables such as surface area, volume and depth, obtained by underwater topographic information. However, this method has a reduced accuracy over time due to the ongoing dynamics of water (Lu *et al*., 2013).

Remote sensing is a cheaper and precise alternative for monitoring reservoirs, considering the increasing number of reservoirs, extensive flooded areas and constant need to obtain information (Abileah *et al.*, 2011; Collischonn and Clarke, 2016; Lopes *et al*., 2017; Machado and Baptista, 2016; Paz *et al*., 2000). Remote sensors allow continuous and systematic collection of data for qualitative and quantitative assessments of the reservoirs that includes, among other things, information about the synoptic view of large areas, trophic condition, possibility to evaluate the spatial variation of evaporation, and higher sampling frequency compared to conventional techniques (Curtarelli *et al*., 2013; Galo *et al.*, 2002; Machado and Baptista, 2016; White, 1978).

Remote sensing data are made available for free by agencies such as NASA (National Aeronautics and Space Administration), USGS (United States Geological Survey), ESA (European Space Agency) and others, with different spatial and temporal scales of the earth's surface, yet robust software, sophisticated equipment for storage and processing data are needed, which prevents the regular monitoring of reservoirs located in different regions (Busker *et al*., 2019; Duan and Bastinnassen, 2013; Gorelick *et al.*, 2017). Google Earth Engine platform (GEE) enables the processing of large amounts of geospatial information from high-performance cloud computing and access to a wide collection of satellite data through user-accessible programming language (Gorelick *et al*., 2017; Nguy-Robertson *et al*., 2018; Zhang *et al*., 2017). GEE allows access and free processing data from orbital satellites, such as Landsat, with considerable time series, allowing reservoir water volume estimation and lakes, indirectly, through mathematical models that use information about the variation of the watercourse extension (Medina *et al*., 2010).

This study there aims to investigate the space-time dynamics of the Serra da Mesa Reservoir using the GEE, from 1998 to 2019, using digital image processing techniques in order to propose a semi-automatic methodology monitoring of Brazilian hydroelectric reservoirs. A secondary goal was to evaluate the seasonality of the reservoir's dry and rainy seasons.

2. MATERIAL AND METHODS

This study was carried out in the hydroelectric plant of Serra da Mesa, located in the basin of the Upper Tocantins in the state of Goiás. The Serra da Mesa includes the municipalities of Minaçu, Campinorte, Campinaçu, Colinas do Sul, Uruaçu, Niquelândia, Barro Alto and São Luiz do Norte, with a total municipal area of 22,366.50 km² and a total flooded area of 1,784.50 km², corresponding to 8% of the cities' area (Figure 1). The reservoir of the hydroelectric plant at Serra da Mesa is classified as an accumulation reservoir and is considered Brazil's largest reservoir volume of water, comprising about 54.40 billion cubic meters. The climate is classified as Aw by Köppen-Geiger, tropical climate, with the lowest temperature above 18°C and a rainy summer.

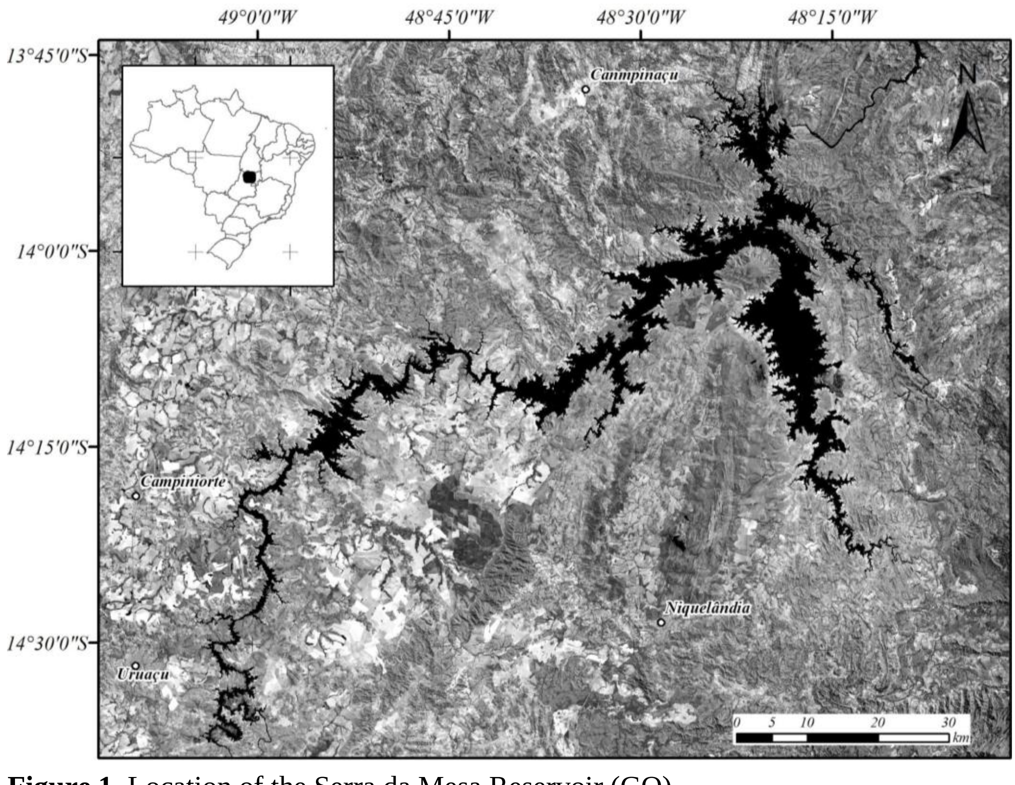

Figure 1. Location of the Serra da Mesa Reservoir (GO).

IPABHi

The watershed of the Upper Tocantins presents, for the most part, a predominance of entisols and inceptisols, as oxisols at lower altitudes and flat regions. According to Martins *et al*. (2015), the predominant geomorphological unit in the basin is the Regional Plain Surface (RPS), characterized by not respecting lithological boundaries or structural styles making several geological units.

For characterization of rainfall in the study area, as well as the variation of maximum temperature (T_x °C) and minimum (T_n ºC), monthly average values were obtained between the years 1998 and 2019 by means of automatic weather stations (AWS) belonging to the National Institute of Meteorology (Instituto Nacional de Meteorologia - INMET). As the city of Minaçu, which locates most of the reservoir, does not have AWS, AWS data closest to the reservoir, located in the municipality of Pirenópolis (GO), were used.

To estimate the reservoir area over the years, data were used from Landsat 5/TM and Landsat 8/OLI available in GEE that allows the manipulation of data by algorithms produced by the operator. In the GEE platform the user can create the data processing routine in Java through an interface, where data can be accessed from various satellites and sensors, with different processing levels. In this study, the SWIR 1, Red and Near Infrared (NIR) spectral bands from the sensors TM (RGB 543) and OLI (RGB 654) were used, with corresponding processing reflectance levels to the top of the atmosphere.

Images between the years 1998 and 2019 were selected, corresponding to the rainy season, considering the months from January to June, and the dry season, from July to December, to characterize the seasonality of the reservoir. Thus, two images were obtained per year, and for the year 2019 only an image related to the rainy season was considered, totaling 43 orbital images in Orbit 222 and Point 070. The previous selection of images in the rainy and dry seasons was to parameter filtering images with less cloud cover and pixels of better quality; this information was obtained from the image metadata. With this information, the algorithm selects the developed image and creates composite RGB bands SWIR1/NIR/R which are later transformed to HSV to identify the pixels corresponding to water. Thus, despite the errors associated with the classification of bodies of water (omission and commission), the objective of this study was to employ a simple methodology using HSV color transformation to assess the potential of Google Earth Engine when comparing the area and the metrics of the reservoir (volume, altimetry and flow).

To validate the data obtained by remote sensing and to fit linear regression models, from the observed data variable volume (m³), altimetric height (m) and the reservoir flow ($m^3.s^{-1}$) through Reservoir Monitoring System (SAR) were obtained, managed by the National Water Agency (ANA), from 1998 to 2019. The data can be obtained on a daily and monthly basis. Since a secondary objective of this study was to evaluate the seasonality of the reservoir's dry and rainy seasons, it was decided to use the semi-scale data, resulting in 43 observations for each variable. To assess the fit of the regression model, we used the coefficient of determination (R^2; Equation 1), adjusted coefficient of determination (R^2_{aj}; Equation 2), standard deviation (S_{xy}; Equation 3) and the standard deviation as a percentage (% S_{xy}; Equation 4).

$$R^2 = 1 - \left(\frac{SQ_{res}}{SQ_t}\right) \quad (1)$$

$$R^2_{aj.} = 1 - \left(\frac{SQ_{res}}{SQ_t}\right) . \left(\frac{n-1}{n-p-1}\right) \quad (2)$$

$$S_{yx} = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n-p-1}} \quad (3)$$

$$S_{yx}\% = \frac{S_{yx}}{\overline{O}} * 100 \quad (4)$$

where, P_i is the ith value estimated by regression; O_i is the ith observed value in monitoring the ANA; $\overline{O}$ is the arithmetic mean of the observed variable; SQ_{res} is the sum of squared residuals; SQ_t is the total sum of squares, n is the number of observed data; p = number of model coefficients.

3. RESULTS AND DISCUSSION

The Serra da Mesa Dam is located in the Upper Tocantins Basin. A watershed has all the elements for the integration of bio-geophysical, economic and social processes and is the natural unit that allows institutional integration and joint research with management (Tundisi, 2008). The expansion of the monitoring scale assists in the management of water resources; that is, when the management considers not only the local, but mainly the basin in which the dam is located, water conservation becomes more efficient. The reflection of this analysis is visible on the dam of Serra da Mesa, where within the same basin were built two new dams, the Cana Brava Dam (2002) and Palmas Dam (2006), whose years of creation coincided with dissonant changes in temporal analysis of share and volume.

Meteorological data show that in the 20 years between 1998 and 2019, the largest volume of rainfall occurred in December 2013, or approximately 501 mm. However, when assessing the average rainfall over 20 years, 2005 had the highest rainfall, about 174 mm, also being the year with the highest cumulative amount of rainfall (2,095.10 mm). With respect to the lower precipitation years, it is observed that in 2002, four years after the construction of the reservoir, there was the lowest average annual rainfall (112.57 mm), the lowest value of accumulated precipitation (1,350.90 mm). This coincided with the year of creation of the Cana Brava Dam, which is located downstream of the Serra da Mesa Dam.

Regarding the average values for temperature, it was observed that the year 2000 had the lowest values Tx and Tn with 30.69°C and 17.56°C, respectively. Already in 2002 there was an increase in the values Tx and Tn, with average values of 31.80°C and 18.38°C, respectively, representing the highest values in the range of 20 years evaluated.

The Serra da Mesa Reservoir, built in 1997, has shown considerable variation in the useful water volume in recent years. The three lower average useful water volumes occurred in 2001 (15.06%) 2016 (12.18%) and 2017 (8.49%) (Figure 2). The useful volume of the reservoir reached 66.76% of total volume in 2011, and had a minimum percentage of useful volume, 10.53% in 2017 (Figure 2A and 2B). These data show that the system behaves differently over the years, even considering that the region has presented regular rainfall. However, there was significant reduction in the useful volume of 2011 and 2017, both in the rainy and the dry seasons (Figure 2A and 2B).

With respect to smaller volumes of water, it is observed that in the years 2003 and 2018 the system had considerable reduction in its volume, being proportional to the surface area values found, 676.23 km² and 632.68 km², in that order. According to Somlyody and Varis (2006), the aggravation and the complexity of water crises stem from an uneven sector process management and response to crisis and problems without predictive attitude and systemic approach (Tundisi, 2008), i.e., the strategy for the creation of new dams should be more comprehensive, considering the current context of the existing dam. An objective dam enjoys a high gap in constant water amount throughout the year because it flattens the natural fluctuations in river discharge (Junk and Mello, 1987). This implies river-level fluctuations, thus creating new dams. Not only the dynamics of rivers is changed, but also of the pre-existing dams. Thus, the decreasing pattern of altimetric height and volume of the Serra da Mesa Dam temporally follows the creation of new dams upstream, and therefore a negative impact resulting from inadequate management of water resources (Figure 2).

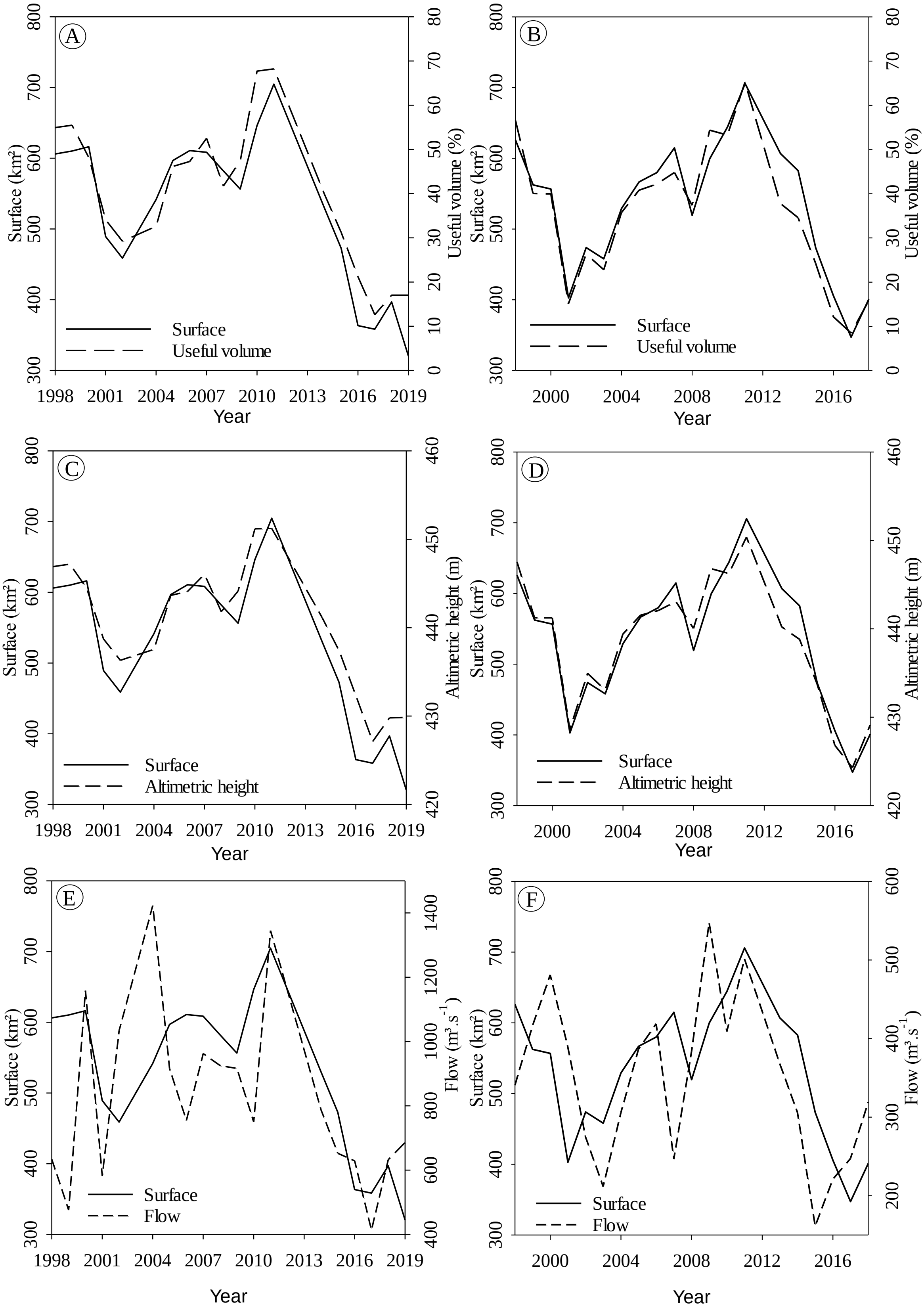

Figure 2. The relationship between the variables (A and B) useful volume (C and D), altimetric height (E and F) and flow in the wet and dry periods, respectively, for the Serra da Mesa Reservoir, GO.

According to National Water Agency (ANA) data, the Serra da Mesa Reservoir (GO) has the highest level of quota (m) in the second quarter of the year, with May showing the highest values compared to other months (Figure 2C and 2D). Through this analysis, the month with the highest share was in April 2012, with approximately 454.34 m. At this time, the useful volume was 78.27% of the total capacity and throughput reached 786.31 $m^3.s^{-1}$ (Figure 2E and 2F). The lowest share was observed in November 2017, reaching 422.39 m, which represents the average volume of 5.92% of its potential reservoir capacity. The most useful volume percentage was observed in 2011, agreeing with the highest average values quota and mirror area of water estimated by means of satellite images that suggested 705.77 km^2 for the full period and 704.79 km^2 for the dry season. The water dynamics in the reservoir may be related to the type of reservoir, as shown in the study conducted in the Barra Bonita Reservoir, Ibitinga and Promissão, located in São Paulo and classified as storage reservoirs. In this study lower water surface was observed in the dry period; different reservoirs of liquid film-type showed an inverse behavior (Galo *et al*., 2002).

Due to areas with shadows or clouds, it was not possible to estimate the reservoir area during the dry season 2003, rainy and dry seasons 2012 and rainy season 2013, preventing the use of this information for the regression fit. Interference caused by clouds in optical images can be avoided when using radar images, which technology allows the survey of areas in different weather conditions (Medina *et al*., 2010; Nguy-Robertson *et al*., 2018). But the constellation of satellites with radar technology does not have global coverage and, in most cases, you need to pay to access the data, different from Landsat and MODIS satellites, that produce images with global coverage and are available for free through government repositories (Nguy-Robertson *et al*., 2018). Even Landsat images are sensitive to the presence of clouds; the great historical images of this project are feasible for monitoring of natural resources.

When observing the rainy season, the estimate of the useful volume and the reservoir altimetric height showed good relationship with the variable area with a determination coefficient above 0.90, making it possible to use the variable area to estimate the useful volume over the years (Medina *et al*., 2010) and assess possible impacts caused by the dynamics of flooding on natural resources and the volume of the reservoir water (Nguy-Robertson *et al*., 2018) (Figure 3A and 3C). The estimate of the surface area of the reservoir by means of satellite images is accurate, and can be used in flood forecasting systems assisting in decision making in the event of imminent disaster (Busker *et al*., 2019). A study developed by Pekel *et al*. (2016) validated the classification with hits for permanent bodies of water, on average, greater than 98% (commission and omission). This work associates errors with smaller water bodies, irrigated fields, floating vegetation and / or hidden by infrastructure such as tunnels and bridges. In the study area, floating vegetation is the only one of these present and is limited to a few arms, representing less than 0.1% of the reservoir, being non-representative.

The estimated flow through the reservoir area hasn't been effective, as the R^2 and R^2aj showed lower values indicating that less than 23% of the reservoir's flow-rate variation can be explained by variation of the reservoir surface area (Figure 3E). Other factors may have a major influence on the reservoir flow, such as volume and depth (Gupta and Banerji, 1985). The result reflects the flow as a way of measurement is susceptible to the method adopted by the operator, which must consider not systematic errors, as well as the transport type, resulting in the release or water retention (Table 1). The low ratio between the area of the reservoir and the flow rate can be observed by the dispersion of waste from the model setting, which showed nearly 55% overestimation in 1999 and 60% by underestimation 2004 (Figure 3F). The regression for volume fit had residual variation between approximately 20% and -20%. This variation was less than 1% for estimating the altimetric height of the reservoir (Figure 3B and Figure 3D).

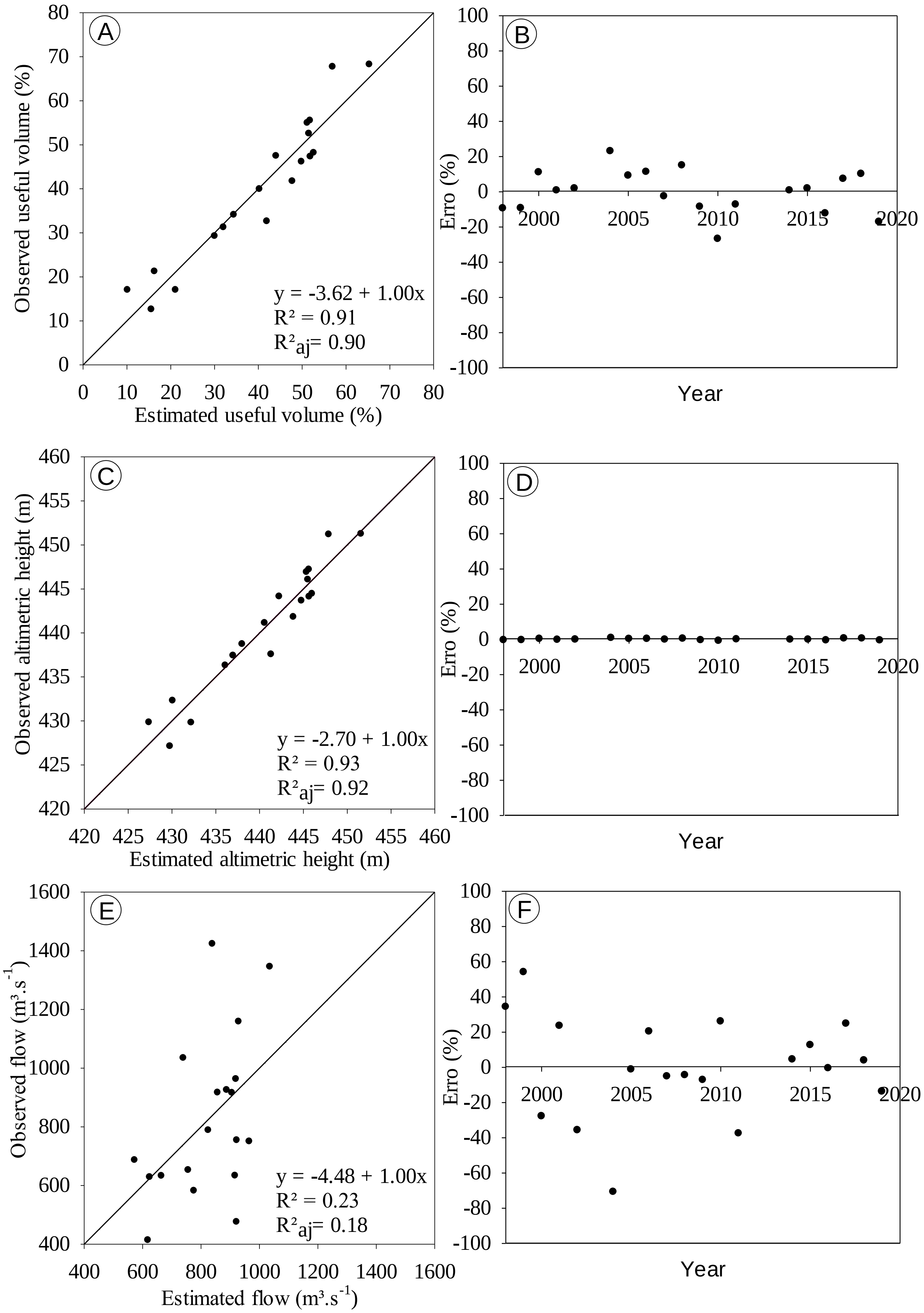

Figure 3. Relationship between observed and estimated data for the variables useful volume (A) altimetric height (C) and flow (E) in the rainy season. Distribution of residues from the set of linear regressions for variables useful volume (B) altimetric height (D) and flow rate (F) in the rainy season.

Table 1. Statistical analysis of the data observed and estimated for the Serra da Mesa Reservoir - GO.

Analysis	Period								
	Rainy			Dry			Yearly		
	Volume	Altimetric height	Flow rate	Volume	Altimetric height	Flow rate	Volume	Altimetri height	Flow rate
Syx	5.09	2.01	247.68	4.30	1.83	86.53	2.96	1.26	59.56
Syx%	12.65	0.46	30.02	12.14	0.42	25.18	7.82	0.29	10.17

* Units: Volume (m^3); Altimetric height (m); Flow ($m^3.s^{-1}$)

During the period of least rainfall, the reservoir has a lower useful volume, with higher average value in 2011 with 65% of its capacity. Over the evaluated years, the useful volume shows small variation in the dry season when compared to the first half of the year, characterized by higher rainfall in the region. This smaller variation of useful volume provides the best linear fit of the useful volume data with the area of the water body, making it possible to explain about 93% of the reservoir's volume change by varying the area occupied by water. Thus, rapid and inexpensive measurements using remote sensing images with high or medium spatial resolution such as Landsat design can be used to estimate the useful volume of the reservoir accurately (Figure 4A and 4B). This information is important for forecasting the water supply potential to the various sectors of society, as well as for assessing and managing the potential for energy production in hydroelectric dams in the event of severe droughts caused by climatic phenomena (Busker *et al*., 2019).

During the rainy season, the variable altimetric height can be estimated accurately, with less than 1% error over the years (Figure 4C and 4D). Even with less variation in the useful volume, due to low rainfall in the period, the flow did not present good seasonal relationship with the reservoir area, with overestimates above 40% in 2007 and 2015, and underestimates greater than 45% in 2009 (Figure 4E and 4F). The flow-rate error was close to 30% in the rainy season and almost 25% in the dry season (Table 1). This high amount may relate to the control of this variable by the reservoir of the operator, with the flow of the reservoir adjusted according to the downstream reservoirs' needs or due to the increased water volume in reservoirs upstream of the Tocantins River Basin (Duan and Bastiaanssen, 2013).

The fitted linear regression model per year, excluding the dry and rainy periods, shows satisfactory for the variable useful volume and flow altimetric height (Figure 5). The relation between the useful volume and the reservoir area is linear, allowing the model to fit with R^2 and R^2_{aj} above 0.90. Thus, it is possible to estimate the useful volume from the reservoir area in any period of the year, with errors in estimated varying between 20% and - 20% approximately (Figure 5A and 5B). The estimate of the useful volume with Landsat images is promising, with error of the estimate of approximately 12%, close to that found by Duan and Basiaanssen (2013) and Muala *et al*. (2014) (Table 1). With this information it is possible to evaluate the impacts caused by climate change and the climatic phenomena El Niño and La Niña on the abstraction of water in lakes and reservoirs (Busker *et al*., 2019) through temporal series of water flow created without the need for *in situ* measurements (Duan and Basiaanssen, 2013).

As with wet and dry periods, the variable altimetric height has a high relationship with the reservoir area and the estimated error is close to zero when annual periods are considered (Figure 5C and 5D). The altimetric height is measured using bathymetry and used to estimate the volume of water in the reservoir. Given the importance of this variable, we need specific equipment and calibration for accurate information, ensuring the medium and long term scheduling of the multiple uses of water. Thus, estimating the reservoir area using satellite images and using cloud processing can be an alternative to assess the quality of data measured in the field, and can identify defective equipment in the reservoir's containment structures. (Busker *et al*., 2019).

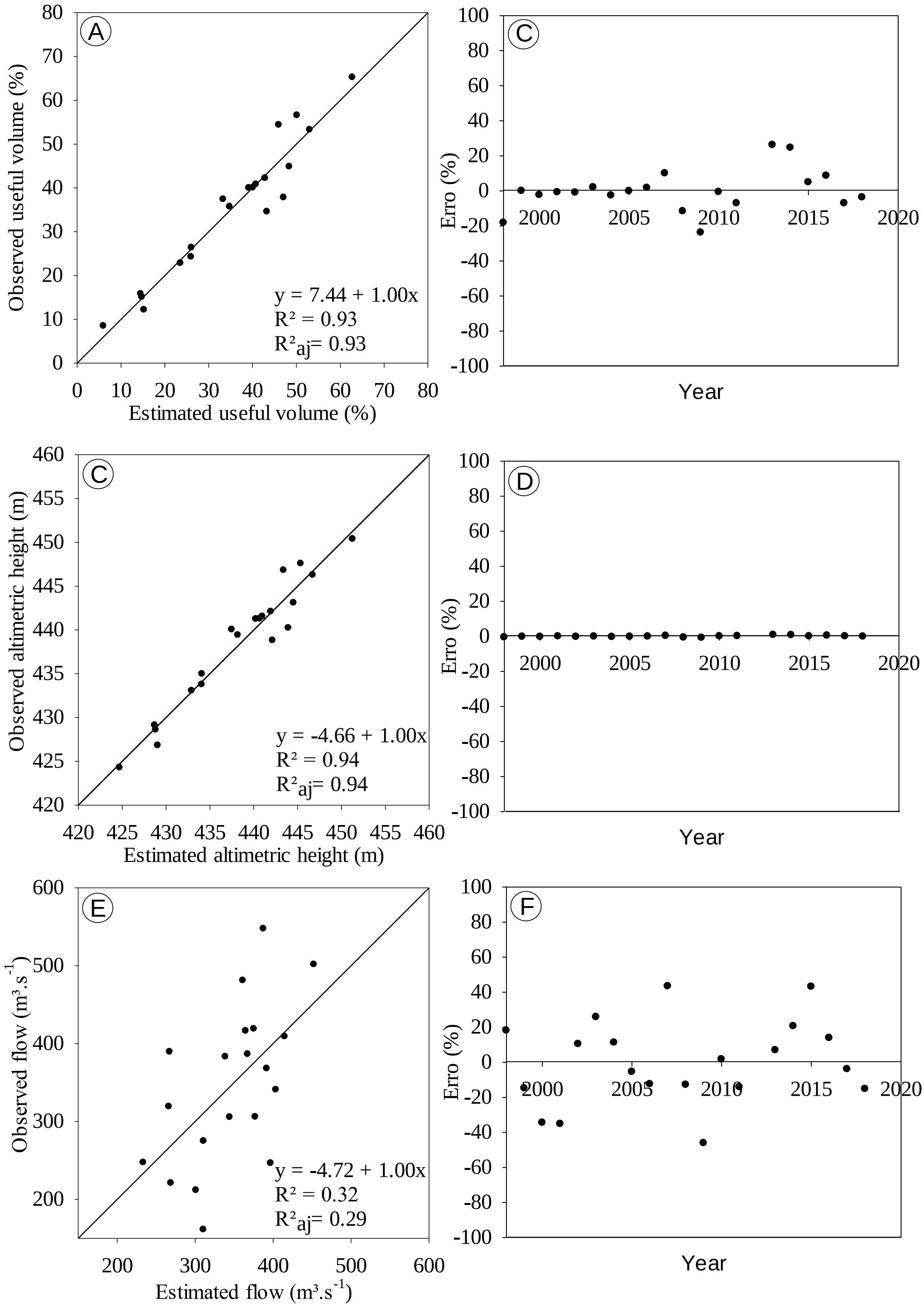

Figure 4. Ratio between observed and estimated data for the variables useful volume (A) altimetric height (C) and flow (E) in dry period. Distribution of residues from the set of linear regressions for useful volume variable (B) altimetric height (D) and flow (F) during the dry period.

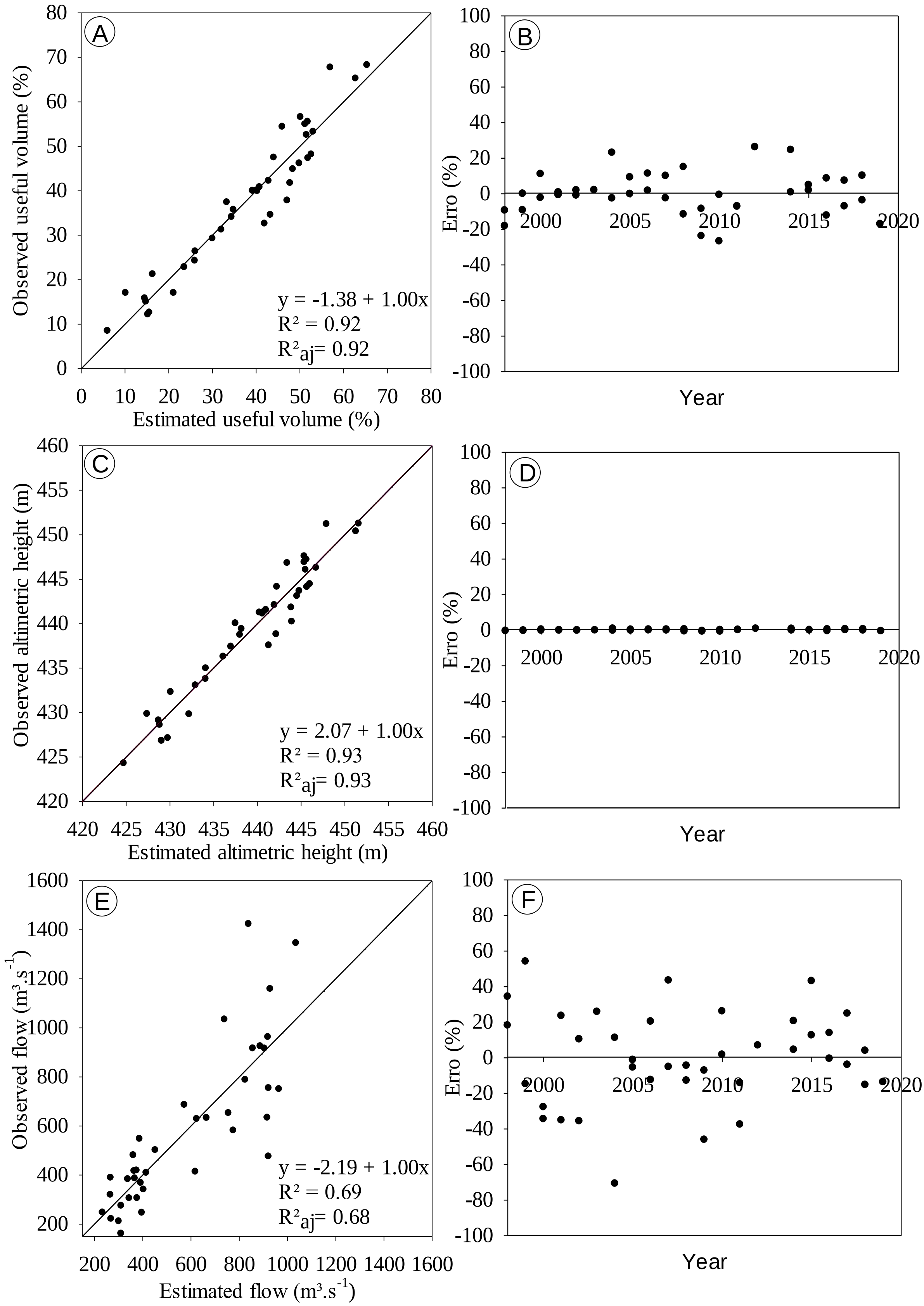

Figure 5. Relationship between observed and estimated data for variables useful volume (a) altimetric height (c) and flow (e) in wet and dry periods. Distribution of residues from the set of linear regressions for varying useful volume (b) altimetric height (d) and flow rate (F) in wet and dry periods.

Figures 3, 4 and 5 show the differences between observed and estimated data in the dry period, the rainy period, and in both together. With this comparison, it is possible to note that the joint analysis of data conforms more closely to flow (R^2 =0.69) compared to separate periods (R^2 =0.18 – 0.29). For the Height and Volume relationships, the period does not influence much; the result was high for all (R^2>0.92).

According to Andrade *et al*. (2015), remote sensing techniques allow the evaluation of the responses derived from human activities and natural processes, in order to predict the impact of these actions on medium and long term sustainability conditions (Novo, 2005). In order to prevent and monitor changes in water resources, the Google Earth Engine platform (GEE) proved itself a powerful tool in the management of natural resources, allowing the processing of large-scale temporal data in a short time. Using this platform, one can access a set of geospatial data and process it with high-performance cloud computing (Gorelick *et al*., 2017), enabling quick and accurate assessments of reservoirs in different environments and facilitating the acquisition of information for more robust studies by entities responsible for water management (Duan and Bastiaanssen, 2013).

4. CONCLUSIONS

Remote sensing is presented as an efficient alternative to water monitoring, due to the inferences that can be made from information from satellite images proportional to the portion of monitoring time series over 20 years in the reservoir of Serra da Mesa (GO). The impact of the GEE platform benefits the management of natural resources, and provides extensive temporal analysis with large amounts of data efficiently in a short time, and has accurate and robust results. In addition, the methodology proposed in this study for height measurement is recommended for other storage reservoirs.

The temporal analysis of the Serra da Mesa Reservoir allows us to observe that there is a pattern of floods and droughts over the years. However, the maximum cost of flooding has been reduced over the years, which shows the reduction of reservoir quotas and water availability for power generation and human consumption. This observed pattern of reduction may reflect the creation of new dams upstream, or also the intensification of land use on the banks of the Serra da Mesa Dam; both explanations originate from anthropogenic action or omission.

Despite the climatic variations that influence dam metrics, anthropogenic factors play important parts in the dam’s history and in the trend. Thus, continuous monitoring of reservoir levels and of the river basin is necessary in order to mitigate potential impacts on the multiple uses of water and find possible alternatives to perpetuate the water supply with minimal impact from flooding.

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