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Dynamics of water level in Bahia reservoirs: an application based on remote sensing

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Abstract: In recent years, in the midst of the drought and water crisis that has affected various regions of Brazil, particularly the semi-arid region, reservoir volumes have been constantly monitored. In this context, the aim of this study was to analyze, using remote sensing, the dynamics of the water mirrors of the reservoirs in Bahia, in order to show how the area of the water mirrors was affected by low rainfall, covering the years 2012 to 2017. To do this, the Google Earth Engine platform was used to analyze Landsat images. To delimit the waters, an enhancement technique was used to convert the RGB images to HVS, creating a panchromatic image and facilitating the process of identifying the water mirrors. The results indicated that the influence of rainfall variability and the impact of other factors reduced the amount of surface water available, so that of the 34 reservoirs studied, 16 had a reduction in their area at the end of the period analyzed. This information is extremely important for the planning and environmental management of water resources, with a view to promoting supply policies and thus increasing the capacity to tackle problems related to water security.
Key words: northeast; water resources; drought; google earth engine; Landsat

1 Introduction

Simply put, in the context of water resource management, water mirrors are the continuous surfaces of water in a body of water exposed to the atmosphere, generally corresponding to the area occupied by that body of water, be it a lake, pond, weir, dam reservoir, etc. (ANA, 2013).

In terms of the importance of water resources, fresh surface waters make up a small fraction of the planet's existing water resources. However, their economic and social value for human populations is inestimable, considering that these waters are the most accessible. In addition, we can say that fresh surface waters provide a diversity of comprehensive ecosystem services for all life (POSTEL et al., 1996; PEKEL et al., 2016).

Reservoirs perform a fundamental service in accumulating water from rainy periods or from the higher flow of water bodies in various hydrographic regions (ANA, 2013). However, the below-average rainfall and extreme drought events observed in recent years (CUNHA et al., 2019) have resulted in a water crisis that has substantially affected several regions of Brazil and, in particular, the semi-arid region from 2012 to 2017.

Thus, the management of surface water reserves is a critical environmental issue, especially in arid and semi-arid regions, and it is important to quantify their spatial and temporal distribution, both locally and regionally (TULBURE and BROICH, 2019). Understanding the spatio-temporal dynamics of surface water bodies is the basis for understanding the effect of rainfall on socio-economic and environmental development (TULBURE and BROICH, 2013).

The dynamics of water loss in Brazil could have worrying consequences, increasing the difficulties for the management and sustainable use of water resources. According to an analysis of satellite images by MapBiomas, Brazil has lost 15.7% of its surface water over the last 30 years, with all biomes, all hydrographic regions and 23 of the 27 states experiencing a reduction in their flooded areas. In addition, the data shows a downward trend in water surface in 8 of the 12 hydrographic regions (MAPBIOMAS, 2021).

In this sense, Remote Sensing offers a range of alternatives for the continuous observation of this natural resource, allowing for various applications, such as the detection, mapping, and bio-optical characterization of water bodies on a large scale (BARBOSA; NOVO; MARTINS, 2019). Satellite measurements and other platforms are also a source of information for mapping the surface waters of the aquatic ecosystem in floodplains, rivers, canals, lakes and reservoirs (SOUZA et al., 2019).

Due to the effect of light absorption, water bodies have a relatively lower spectral reflectance than other surface targets in the visible and infrared spectrum, making water bodies easily detectable (YAN et al., 2019). Thus, there are several remote sensing techniques for identifying bodies of water (ELSAHABI et al., 2016). This set of possibilities ranges from the use of various spectral indices (DU et al., 2016); and types of sensors, whether active (PHAMDUC et al., 2017) and/or passive (MUELLER et al., 2016); of different spatial (CHEN et al., 2018), spectral and temporal resolutions (COOLEY et al., 2017).

Other examples are applications in research for classifying water bodies (KO et al., 2015); monitoring water quality (XU et al., 2021), volume in reservoirs (DUAN and BASTIAANSSEN, 2013), spatial and global water dynamics (PICKENS et al., 2020) and territorial mapping (MOREIRA, 2002; MOREIRA et al., 2018).

The potential for using remote sensing to study and monitor water resources is therefore very diverse and highly relevant. In this sense, remote sensing techniques and their products have shown great potential for monitoring and managing water resources in recent decades. In addition, it is still capable of monitoring and analyzing large areas in less time and more cost-effectively with the advent of cloud computing and Big Data.

Therefore, given the large number of reservoirs in Bahia and the importance of water resources for socio-economic development, the purpose of this work was to map and analyze, using Remote Sensing, the dynamics of the water mirrors of the main reservoirs in the state of Bahia, in order to show how the area of the reservoirs' water mirrors were affected by below-average rainfall during the last six years of drought in the Northeast Region of Brazil, from 2012 to 2017.

2 Characterization of the study area

The study area encompasses the main reservoirs in the main hydrographic regions of Bahia, as shown in Figure 1. The state of Bahia is divided into 77 regions with relatively homogeneous characteristics called Balance Units (UB), thus characterizing the State Hydrographic Division, made up of 13 Hydrographic Basins (PERHBA, 2005).

In the 13 hydrographic divisions (São Francisco, Vaza-Barris, Itapicuru, Real, Paraguaçu, Inhambupe, Recôncavo Norte, Recôncavo Sul, Contas, Pardo, Leste, Jequitinhonha and Extremo Sul), several reservoirs were built in order to create surface water reserves to promote the multiple use of water and reduce vulnerability to droughts and floods.

In this way, the strategic reservoirs for supplying the state of Bahia with a water capacity of over 14 million m³ were mapped. This information was collected from data made available by the National Water Agency (ANA), the National Department for Works Against Droughts (DNOCS) and the Institute for the Environment and Water Resources (INEMA).

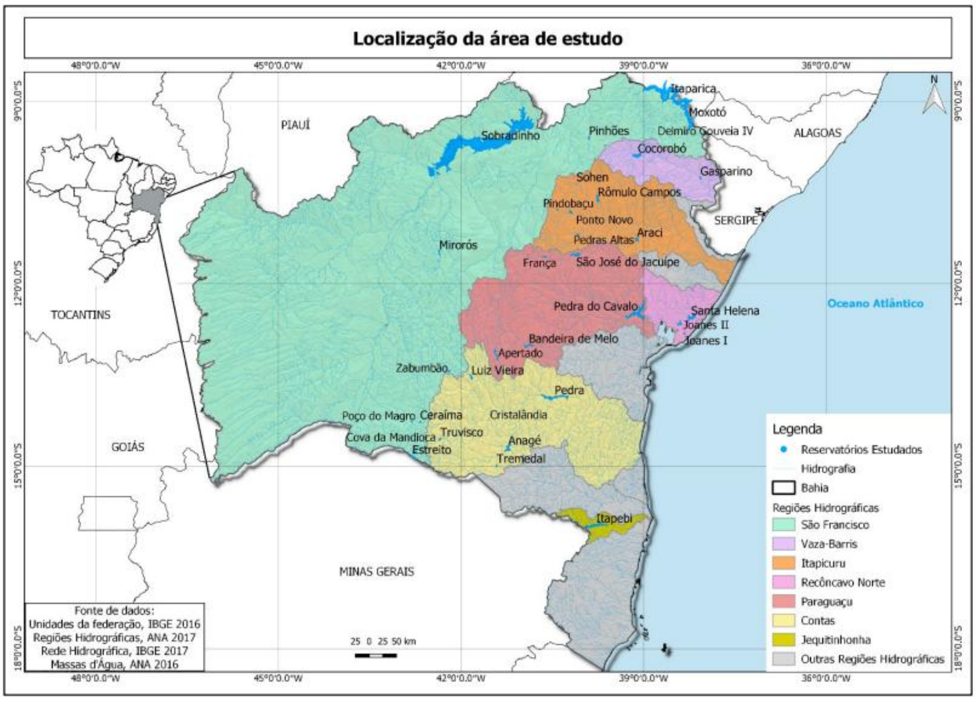

Figure 1. Location of reservoirs, drainages and boundaries of Bahia's river basins

Source: Prepared by the authors, 2022

2.1 Geo-environmental factors

The disposition of surface and groundwater resources depends on many mutual relationships, above all the integration of climatic, geomorphological and geological factors. Added to this are the changes made by human activities, such as multiple land uses, dam construction, water transposition, etc. Thus, the integrated analysis of the physical environment by these factors allows for a better understanding of geological-environmental relations and the behavior of water reserves in the face of drought events.

The state of Bahia has a predominantly semi-arid climate, representing around 68% of the total area, characterized by low annual rainfall. This climate type is found mainly in the northern and northeastern mesoregions of the state, as well as in some parts of the São Francisco Valley, Chapada Diamantina and southwestern mesoregions of the state. Its main characteristics are average annual temperatures above 24ºC, with annual rainfall of less than 700mm and long periods of drought (INEMA, 2009).

In the other regions, rainfall is above 1,000 mm, characterizing tropical rainy climates in the south and west of the state and in the recôncavo mesoregion. The high-altitude tropical climate typology occurs in the central part of the state in areas with higher topographic elevation, such as the Diamantina plateau and the Espinhaço and Jacobina mountain ranges. In simplified terms, Bahia is characterized by the presence of three types of climate: rainy tropical, high altitude tropical and semi-arid, as can be seen in Figure 2.

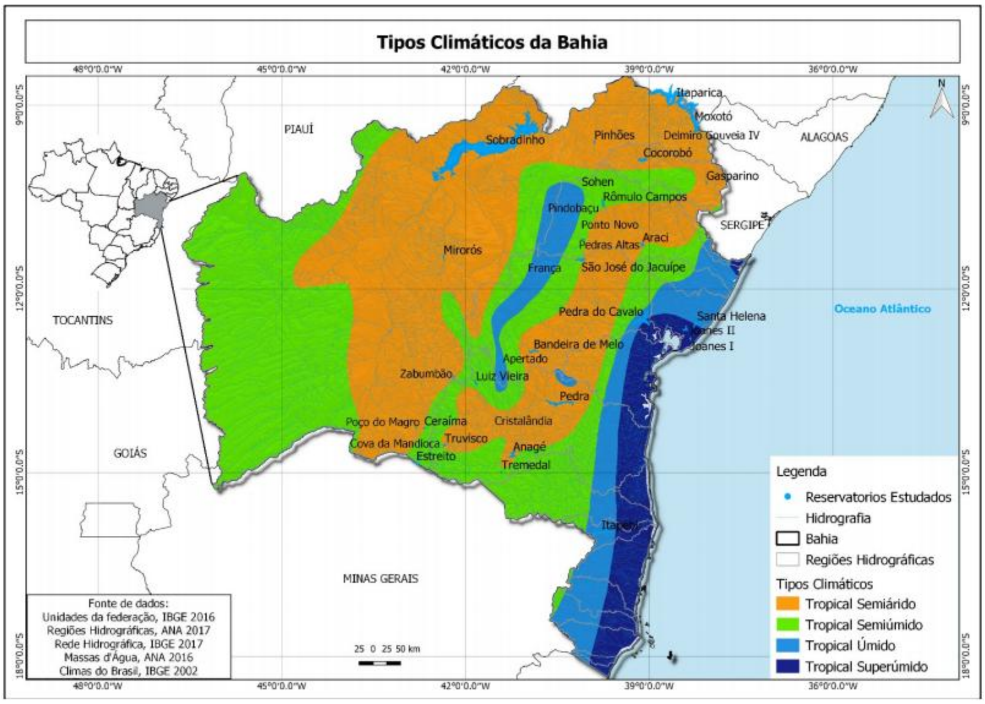

Figure 2. Climatic types in the state of Bahia Source: adapted from IBGE, 2002

In terms of relief, Bahia has the characteristics of a set of geological and geomorphological factors. Its territory includes low and medium altitude regions in the peripheral depressions, the Interplanaltic and the coast; as well as higher altitude areas such as the Jequitinhonha plateau in the south of Bahia, the pre-littoral plateaus, the Diamantina and western São Francisco plateaus, as well as the Serra Geral do Espinhaço and Jacobina. Its complex geological structure can be simplified into groups of crystalline rocks and sedimentary rocks. The latter occupy most of the state, as can be seen in Figure 3.

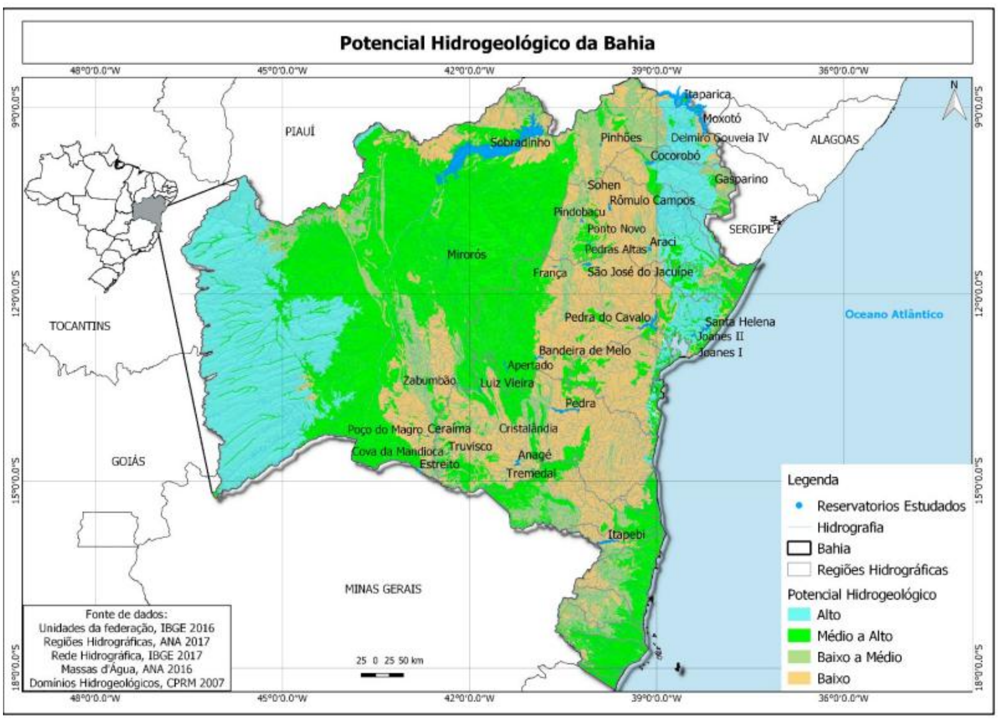

Figure 3. Map of the hydrogeological potential of the state of Bahia Source: adapted from CPRM, 2007

3 Materials and methods

In order to carry out spatial and temporal mapping of the behavior of the water bodies of the main surface water reserves in the state of Bahia during the period from 2012 to 2017, in which below-average rainfall was recorded, the Google Earth Engine (GEE) platform was used, an advanced cloud-based geospatial processing platform designed primarily for environmental data analysis on a planetary scale (big data); as well as QGis, a free Geographic Information System (GIS) for data visualization, editing and analysis.

A set of images from the Landsat 7 and Landsat 8 satellites were used as remote sensing products. The GEE loaded the images from the Landsat 7 satellites for the years 2012 and 2013, and Landsat 8 for the years 2014 to 2017. Then, the RGB 3-4-5 color composition was made for the ETM/Landsat 7 sensor images, and 6-5-4 for OLI/Landsat 8.

To geoprocess the data, image sets from the Landsat 7 and 8 satellites were used. The Landsat 7 images covered the period from 2012 to 2013 and the Landsat 8 images the period from 2014 to 2017. The image compositions were worked on separately in different scripts, year by year. Thus, as a criterion for selecting the images, filtering was carried out by date (filterDate) covering a one-year interval (01-01-201X to 31-12-201X) and by geometry (filterBounds), which included the boundaries of the state of Bahia. Then the .map command was applied to process the cloud mask for all the scenes in the composition and, finally, the median of the composition was returned, generating the annual mosaic to be worked on.

With regard to cloud masking, a simplified process was applied to reduce the influence of cloud cover on image composition. To do this, the ee.Algorithms.Landsat.simpleCloudScore algorithm was used, which calculates a simple cloud probability score in the range of 0 to 100 using a combination of brightness, temperature and Normalized Difference Snow Index (NDSI). In this study, the threshold value for cloud probability was set at less than 70.

Then the RGB 3-4-5 color composite was used for the ETM/Landsat 7 sensor images, and 6-5-4 for the OLI/Landsat 8. Next, in order to determine areas with a water surface, known as "water mirrors", the RGB to HSV (IHS or HLS) (Intensity, Hue, Saturation) image conversion technique was used, creating a panchromatic (black and white) image using the Hue component.

The extraction of water bodies using this enhancement technique consists of disaggregating the spectral information into the Hue and Saturation components, and the spatial information into the Intensity component, helping to highlight objects and features (Florenzano, 2011).

In this way, the hue band was used to generate a panchromatic image with information on the surface targets where water bodies differ from other targets, facilitating the process of identifying and extracting water mirrors.

The application of procedures for identifying and extracting information for mapping surface water reserves using the enhancement technique of converting RGB images from Landsat satellite sensors to HSV is an active and widely known methodology, and was therefore used in this study.

The images corresponding to the Hue values (water mirrors) of the study area were then exported from GEE. The matrix data was then imported into QGIS for processing and quantification of the water mirror areas.

This made it possible to carry out a preliminary visual analysis of the dynamics of the contraction and expansion of the bodies of water over the six years mapped, as well as to support the quantitative analysis of these changes. Graphs, tables and thematic maps on the spatial and temporal behavior of the water bodies were then drawn up using the occupied area data. The mapping and quantification of the areas made it possible to observe the behavior and dynamics of the gain and loss of water bodies in Bahia.

In addition, in order to be able to relate the dynamics of the water bodies to the rainfall data, graphs were drawn up of the average annual rainfall in the reservoirs from 2011 to 2017, using data from 47 rain gauge stations available on the

ANA's HidroWeb website (https://www.snirh.gov.br/hidroweb/mapa). It should be noted that 2011 was chosen as the base year for the analysis of the time series of average annual rainfall, as it was understood that the behavior of the reservoir areas in 2012, the base year for mapping the water mirrors, co uld only be fully understood with the rainfall information from the previous year (2011), also helping to interpret the entire time series of rainfall and its possible correlations with the decrease or growth of the water mirror areas.

A total of 34 reservoirs were mapped, eleven in the São Francisco river basin, six in the Contas river basin, six in the Itapicuru river basin, five in the Paraguaçu river basin, three in the Recôncavo Norte basin, two in the Vaza-Barris basin and one reservoir in the Jequitinhonha river basin. The results of all the mapping are available on the website of the Geoprocessing Group of the Northeast Space Coordination (COENE) of the National Institute for Space Research (INPE): http://geopro.crn.inpe.br/RH_reser_Bahia.htm.

4 Results and discussion

Table 1 shows the mapped water mirror areas for each year, as well as the percentage change in area (gain or loss) during the period studied, based on 2012, and the water capacity of the reservoirs.

The results showed that of the 11 reservoirs mapped in the São Francisco river basin, five dams, namely: Delmiro Golveia IV, Itaparica, Moxotó, Sobradinho and Zabumbão, lost water mirror area during the period analyzed.

In contrast to the reservoirs that have seen a reduction in water surface area, it is worth highlighting the reservoirs that have seen a gain in area: Ceraíma, Cova da Mandioca, Estreito, Mirorós, Pinhões and Poço do Magro. With regard to the Poço do Magro reservoir, its water mirror increased significantly in 2013 compared to the previous year. This reservoir saw an increase of approximately 5,000% in its area compared to the base year of 2012.

This growth may be associated with various factors, such as concentrated rainfall in the sub-basin of this reservoir. In addition, the geographical location of the reservoirs within the river basin (upper, middle and lower reaches) may also explain the variations in reservoir area that cannot be elucidated solely on the basis of the basin's average annual rainfall data.

Table 1. Temporal variation in the areas of the water mirrors of the São Francisco basin reservoirs

Reservoirs	Capacity (m³)	Water Mirror Areas (Km²)						Percentage change in area: (+) Gain (-) Loss
		2012	2013	2014	2015	2016	2017	
Ceraíma	58.000.000	1,17	0,95	2,75	3,54	4,52	4,38	+ 274,36
Cova da Mandioca	126.010.000	1,98	2,23	8, 16	5,51	9,29	6,99	+ 253,03
Delmiro Golveia IV	127.500.000	13,53	11,41	13,51	13,68	13,44	13,30	- 1,70
Estreito	67.560.000	2,80	3,06	4,68	3,40	6,47	5,20	+ 85,71
Itaparica	10.782.000.000	716,72	652,47	648,22	621,02	630,89	615,88	- 14,07
Mirorós	158.400.000	1,43	1,15	1,73	1,65	2,73	2,07	+ 44,76
Moxotó	1.277.000.000	73,98	67,40	73,47	72,66	71,53	68,29	- 7,69
Pinhões	15.215.750	1,59	1,30	4,64	2,66	4,02	1,64	+ 3, 14
Poço do Magro	37.000.000	0,07	0,09	2,55	4,21	4,44	3,81	+ 5.342,86
Sobradinho	34.116.000.000	2.740,34	2.330,24	2.430,78	1.732,82	1.823,63	1.507,30	- 45,00
Zabumbão	60.853.000	2,65	2,06	2,32	2,49	2,70	2,28	- 13,96

Source: Authors

The information in the graph of the average annual rainfall in the reservoirs' catchment areas from 2011 to 2017 (Figure 4) helps us to understand the dynamics of these reservoirs' water bodies, given that rainfall directly affects them.

From the perspective of changes in the rainfall regime and climate variability, Paredes-Trejo et al. (2021) carried out an assessment of droughts in the São Francisco River basin using Terrestrial and Satellite Indices, from 1980 to 2015, and observed a drying trend on an annual time scale in the middle and southern regions of the basin and an expansion of the area under drought conditions only during the winter months of the southern hemisphere, demonstrating that drought conditions were worsening in terms of frequency, spatial extent, duration and severity.

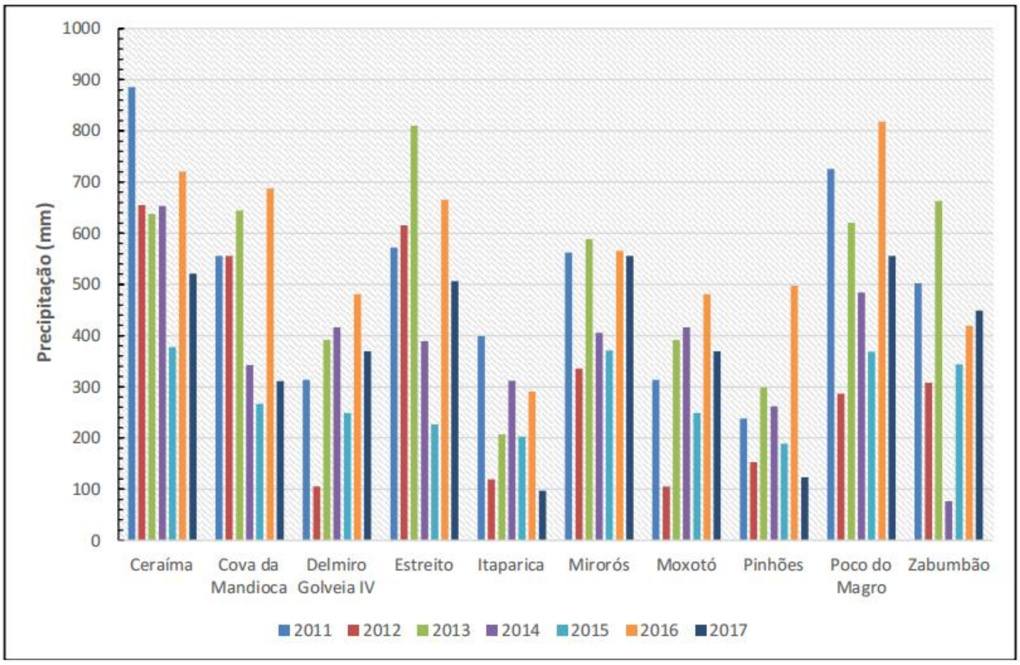

Figure 4. Average annual rainfall over the São Francisco reservoir basin from 2011 to 2017 Source: adapted from ANA, 2022

This information helps to understand the reduction in flooded areas shown by some reservoirs in the São Francisco basin. Among the reservoirs that lost water mirror area, Sobradinho showed the greatest reduction, despite having the largest water capacity for the São Francisco basin (34,116 hm³), losing 45% of its area. Itaparica showed the second biggest reduction, with approximately 14%, followed by Zabumbão, Moxotó and Delmiro Golveia IV with 13.96%, 7.69% and 1.70%, respectively.

Still with regard to dynamics, it is worth highlighting the Sobradinho, Itaparica, Moxotó and Delmiro Golveia IV reservoirs, which have a spatial distribution in successive order and a cascade operating regime. With regard to this regime, Barbosa et al. (1999) pointed out that the configuration of these reservoirs in successive order in the same river course and arranged in a sequence, shows significant dependence on each other, with implications for the water quality.

In this case, this operating system directly affects the volume and sometimes the water mirror, since part of the lakes in some of these reservoirs are dammed in canyons, where it is difficult to establish a relationship between volume and flooded area using medium-resolution optical satellite images. Thus, the dynamics of the flooded areas of the middle/lower São Francisco are not only affected by the spatial and temporal variability of rainfall, but also by the allocation of water between the reservoirs for the water transposition project, as well as by the geomorphology in which the reservoirs are located.

In this context, the information in the graph (Figure 5) of average annual rainfall for the period 2011 to 2017 from the climatological stations upstream of Sobradinho (Figure 6), in the upper and middle reaches of the São Francisco River, helps to explain the dynamics of the annual gain and loss of area observed in this reservoir.

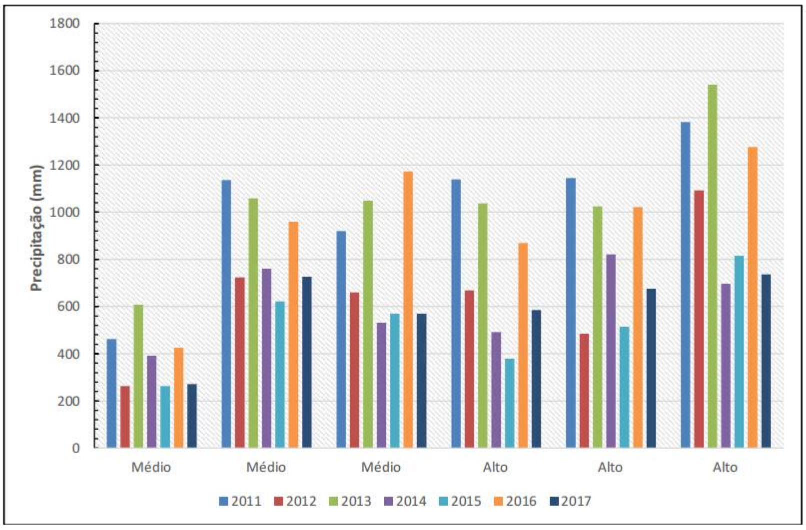

Figure 5. Average annual rainfall over the basin upstream of Sobradinho from 2011 to 2017 Source: adapted from ANA, 2022

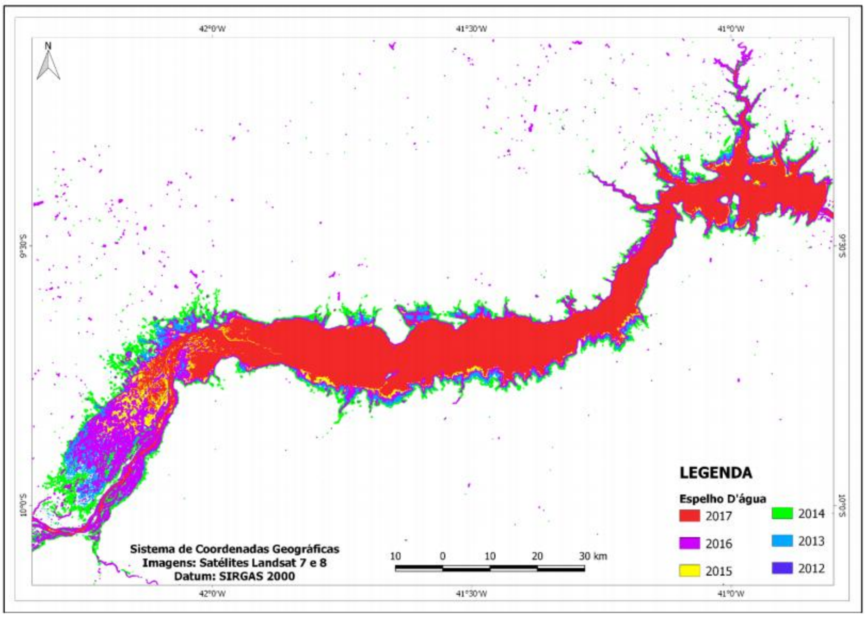

Figure 6. Dynamics of the water mirror of the Sobradinho reservoir, Bahia Source: Research results, 2022

In the Contas river basin, located in a region with a predominantly semi-arid climate, almost all the reservoirs showed an increase in their water levels. Only the Luiz Vieira dam showed a reduction of just over 3%, as can be seen in Table 2.

Table 2. Temporal variation in the water mirror areas of the Contas basin reservoirs

Reservoirs	Capacity (m³)	Water Mirror Areas (Km²)						Variation percentage of area: (+) Gain and (-) Loss
		2012	2013	2014	2015	2016	2017	
Anagé	255.630.000	7,79	6,02	12,48	13,17	13,77	11,62	+ 49,17
Cristalândia	16.650.300	1,57	1,98	1,77	1,72	1,39	1,78	+ 13,38
Luiz Vieira	105.000.000	2,64	2,17	2,22	2,76	3,16	2,54	- 3,79
Pedra	1.640.000.000	42,95	40,85	55,21	58,77	69,57	48,93	+ 13,92
Tremedal	23.751.000	0,93	0,63	1,69	1,85	2,14	2,11	+ 126,88
Truvisco	38.949.800	0,95	1,17	2,02	1,84	1,84	1,35	+ 42,11

Source: Authors

In the context of the Contas basin, the reservoirs that increased their water mirror were Anagé, Cristalândia, Pedra, Tremedal and Truvisco. The Tremedal dam (Figure 7) showed an increase in 2014, reaching a total of 126.88% at the end of the period.

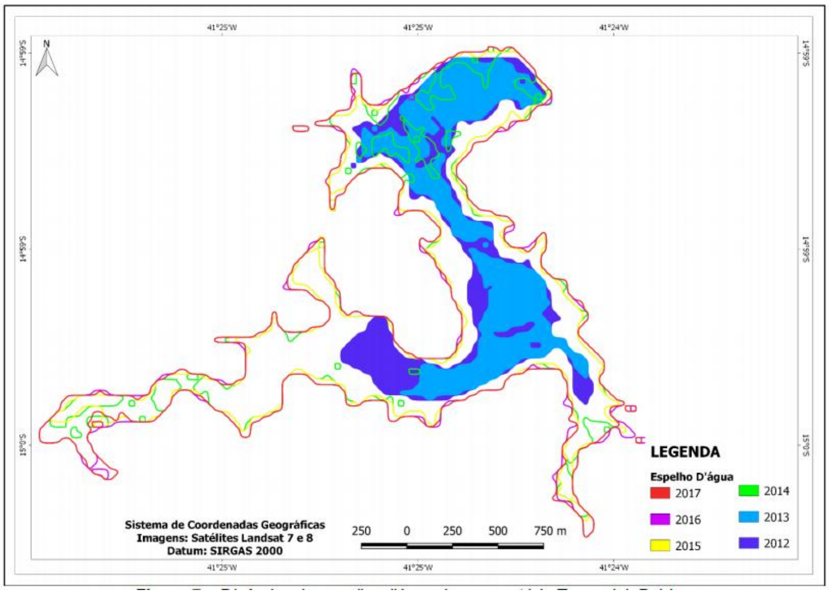

Figure 7. Dynamics of the water mirror of the Tremedal reservoir, Bahia

Source: Research results, 2022

Analyzing the behavior of rainfall in the reservoirs in this basin can help us understand the dynamics observed in these reservoirs. In addition, it is possible to see a significant reduction in rainfall in 2012 in almost all the reservoirs when compared to the previous year, as can be seen in Figure 8.

Another important basin, located in the northeastern mesoregion of Bahia, is the Itapicuru River basin. The basin has a semi-arid climate over 81% of its area, with annual rainfall of less than 700 mm. In the upper reaches of the basin, in the Chapada da Diamantina, the climate becomes milder, changing to sub-humid to dry, with rainfall totals reaching up to 900 mm. In the lower part of the basin, the climate changes to humid to sub-humid with rainfall of over 1,000 mm. With regard to the geological and geomorphological domains, it has high slope terrain; areas of crystalline geological domain; terrain associated with the Recôncavo Tucano sedimentary basin and crystalline areas near the coast (INEMA, 2021).

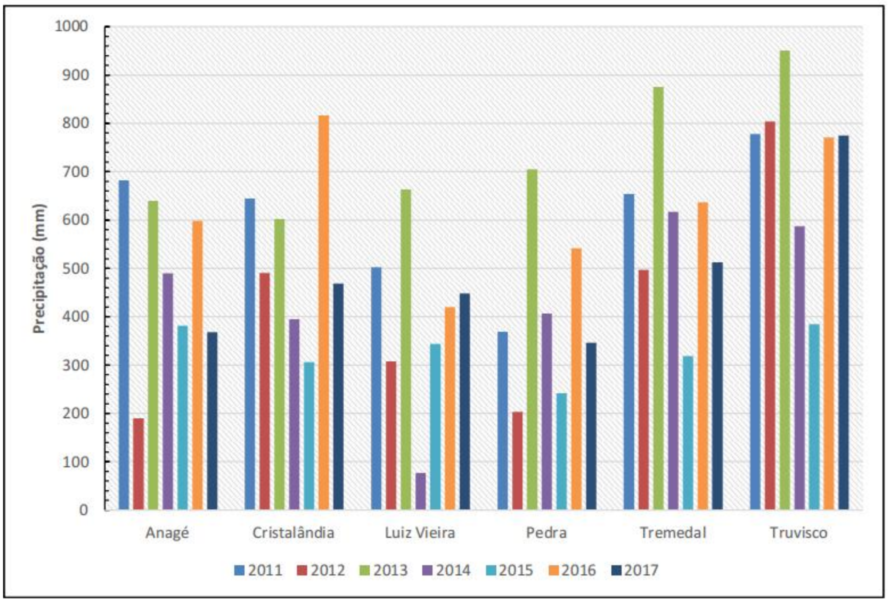

Figure 8. Average annual rainfall over the basin of contribution of the Contas basin reservoirs from 2011 to 2017

Source: adapted from ANA, 2022

In this basin, six reservoirs were analyzed, of which only Rômulo Campos and Sohen showed an increase in the water mirror. From this perspective, the Rômulo Campos dam (Figure 9) showed this gain scenario, compared to the 2012 period, from the 2014 period onwards. The Sohen dam showed the greatest percentage gain in this basin, as shown in Table 3.

Table 3. Temporal variation of the water mirror areas of the Itapicuru basin reservoirs

Reservoirs	Capacity (m³)	Water Mirror Areas (Km²)						Percentage area change: (+) Gain and (-) Loss
		2012	2013	2014	2015	2016	2017	
Araci	65.839.200	6,57	5,38	4,50	3,53	7,13	4,65	- 29,22
Pedras Altas	38.450.000	2,59	1,74	2,46	3,16	3,37	1,34	- 48,26
Pindobaçu	16.800.000	0,98	1,27	0,99	1,14	1,13	0,91	- 7,14
Ponto Novo	38.940.000	3,16	5,66	5,03	5,60	4,47	2,74	- 13,29
Rômulo Campos	146.819.000	4,96	2,09	5,02	4,48	17,26	13,94	+ 181,05
Sohen	14.856.000	0,12	0,67	0,64	0,60	1,35	1,16	+ 866,67

In the same basin, the Araci reservoir, the second largest reservoir in this basin, although it has the capacity to accumulate a large amount of water, 65 million m³, lost almost 30% of its area over the six years evaluated. The Pedras Altas reservoir, on the other hand, had the highest percentage loss in this basin at almost 50%. Among the reasons contributing to this scenario are possibly the sum of factors such as: location in a semi-arid climate region and crystalline geology; as well as low rainfall events in the sub-basin linked to this reservoir.

Areas of crystalline geology, which are very common in northeastern Brazil, have low porosity and permeability when compared to regions of sedimentary geology, which ends up making it difficult to store groundwater and form a network of perennial rivers, especially in regions with a semi-arid climate. These characteristics mean that surface water is quickly carried to reservoirs, where it is largely lost through direct evaporation, affecting water availability. On the other hand, in places with a sedimentary geological structure, rainwater supplies soils and aquifers, where water is released into surface water reserves gradually, which reduces its exposure to solar radiation and loss through evaporation.

According to the ANA (2017), the magnitude of high evaporation rates induced by temperature, with annual totals of more than 2,000 mm, can cause a reduction in the water of lakes, dams and reservoirs, representing up to 1/3 of the average affluent flow being consumed annually by the exposure of water bodies.

The graph in Figure 10 shows that in 2012 there was a reduction in the average annual rainfall over the catchments of the Itapicuru basin reservoirs. This reduction was almost half the amount compared to the previous year, 2011.

In the Paraguaçu River basin, an important basin in the central-western mesoregion of Bahia, the dynamics of water mirror area loss in five reservoirs were analyzed (Table 4). Considering the dynamics of area loss, the Apertado dam showed the greatest reduction, losing almost 50% of its water mirror.

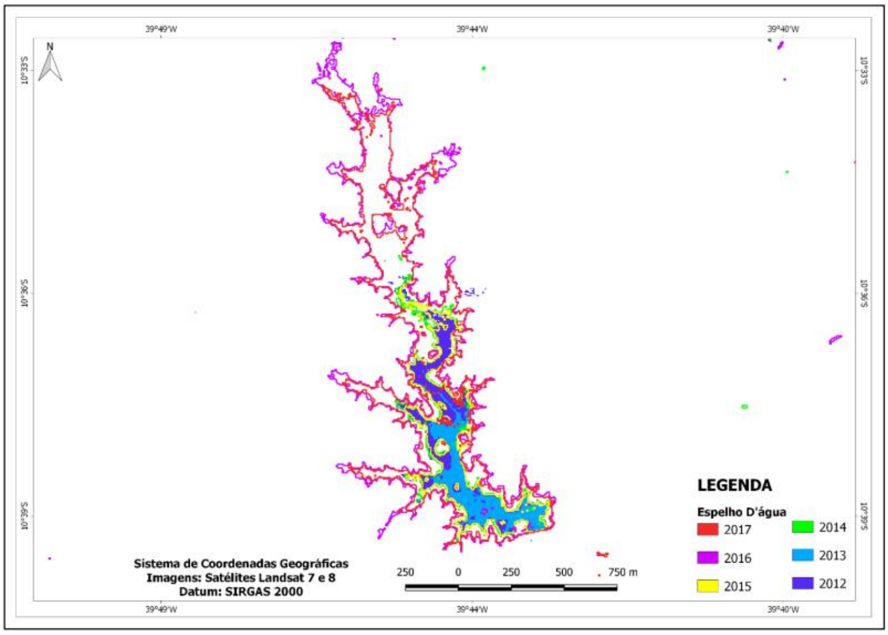

Figure 9. Dynamics of the water mirror of the Rômulo Campos reservoir, Bahia Source: Research results, 2022

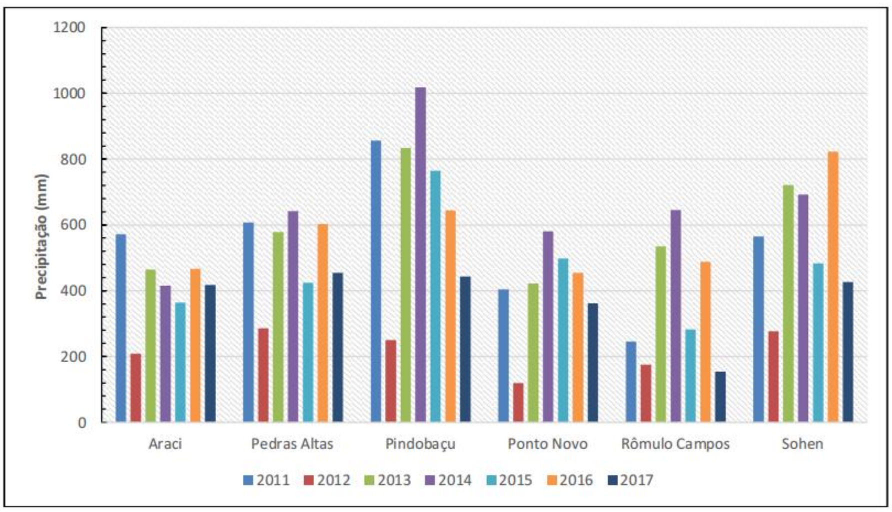

Figure 10. Average annual rainfall over the catchment area of the Itapicuru basin reservoirs from 2011 to 2017

Source: adapted from ANA, 2022

Table 4. Temporal variation in the water mirror areas of the Paraguaçu basin reservoirs

Reservoirs	Capacity (m³)	Water Mirror Areas (Km²)						Percentage change in area: (+) Gain and (-) Loss
		2012	2013	2014	2015	2016	2017	

Apertado	108.690.000	7,45	5,84	6,01	6,27	5,78	3,88	- 47,92
Bandeira de Mello	111.590.000	16,44	17,09	18,17	18,20	17,34	17,91	+ 8,94
França	33.170.000	1,28	1,79	1,91	3,44	3,29	2,22	+ 73,44
Pedra do Cavalo	4.630.960.000	105,71	87,84	99,04	101,38	93,86	96,33	- 8,87
São José do Jacuípe	357.000.000	7,83	4,93	4,76	3,81	10,57	7,18	- 8,30

Source: Authors

In the general context, although the semi-arid climate predominates in 67% of the basin (INEMA, 2021), the Bandeira de Mello and França reservoirs have increased their area. Also noteworthy is the low percentage of loss in Pedra do Cavalo and S. J Jacuípe (Figure 11).

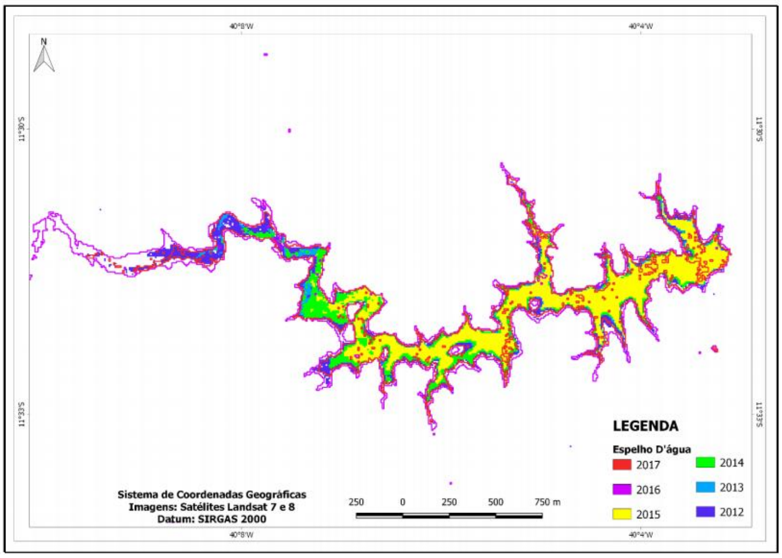

Figure 11. Dynamics of the water mirror of the São José do Jacuípe reservoir, Bahia. Source: Research results, 2022

These behaviors may be linked to the influence of climate variability on the accumulated rainfall in the sub-basins of these reservoirs, since some of them are totally inserted in a rainfall region with a more humid climate, such as the tropical humid highlands.

In this region, the climate becomes milder, changing to the semi-humid to humid type, with some small areas at the source of the Paraguaçu River presenting a humid to sub-humid climate, where rainfall totals increase, reaching up to 1,200 mm (INEMA, 2021). This geomorphological compartment with its higher topographic elevation causes occasional orographic rainfall and influences the hydrographic regions of the semi-arid domains surrounding the plateau, directly affecting surface water reserves.

In addition, the geographical location of the reservoirs within the river basin (upper, middle and lower reaches) can also explain the variations in the area of the reservoirs, which cannot be elucidated solely on the basis of average annual rainfall data for the basin and reservoirs, since many of the weather stations are located in areas surrounding mountainous regions and are therefore unable to record rainfall due to the terrain, orographic rainfall.

Figure 12 shows the reduction in rainfall in 2012 for almost all the reservoirs, when compared to the rainfall in 2011. The other years in the series (2013 to 2017) showed values equal to or greater than those seen in 2011 and helped to understand the dynamics of the area presented by the reservoirs in the Paraguaçu basin.

In the areas of the basins closer to the coast and with a more humid climate, such as the Recôncavo Norte basin, the reservoirs managed to maintain their water mirror throughout the period analyzed. Even so, all three reservoirs lost area, with the Joanes I dam showing the greatest loss, with just over 55% of its area, as can be seen in Table 5.

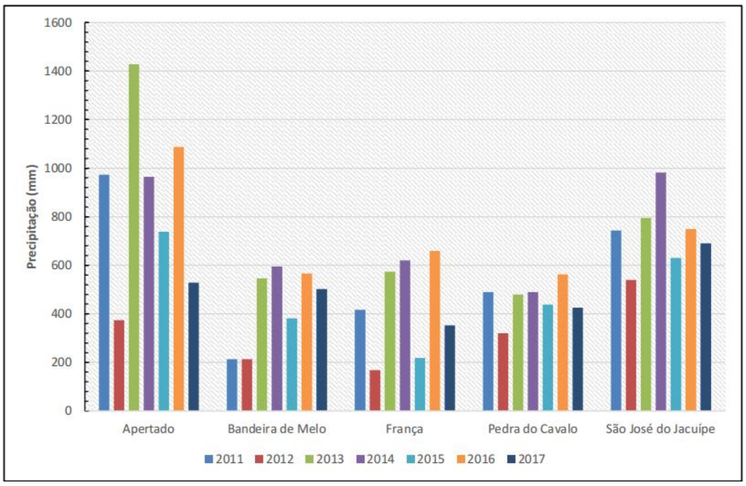

Figure 12. Average annual rainfall over the catchment area of the Paraguaçu basin reservoirs from 2011 to 2017

Source: adapted from ANA, 2022

Table 5. Temporal variation in the areas of the water mirrors of the reservoirs in the Recôncavo Norte basin

Reservoirs	Capacity (m^3)	Water Mirror Areas (Km^2)						Percentage change in area: (+) Gain and (-) Loss
		2012	2013	2014	2015	2016	2017	
Joanes I	19.000.000	0,87	0,81	0,42	0,63	0,60	0,39	- 55,17
Joanes II	128.000.000	12,25	11,56	12,00	12,02	7,64	6,63	- 45,88
Santa Helena	241.000.000	22,14	20,82	18,80	19,83	17,01	17,00	- 23,22

Source: Authors

The other reservoirs, on the other hand, showed a percentage loss of area below 50%, with Joanes II losing approximately 45% and Santa Helena 23.22% (Figure 13). In this context of loss, several factors can influence the results observed. Thus, in addition to the climate, the local physiography (hydro-geological potential and geomorphology), as well as the water management of its watershed, such as flow control for preventive actions to ensure the safety of dams, are the possible explanations for the loss of area observed.

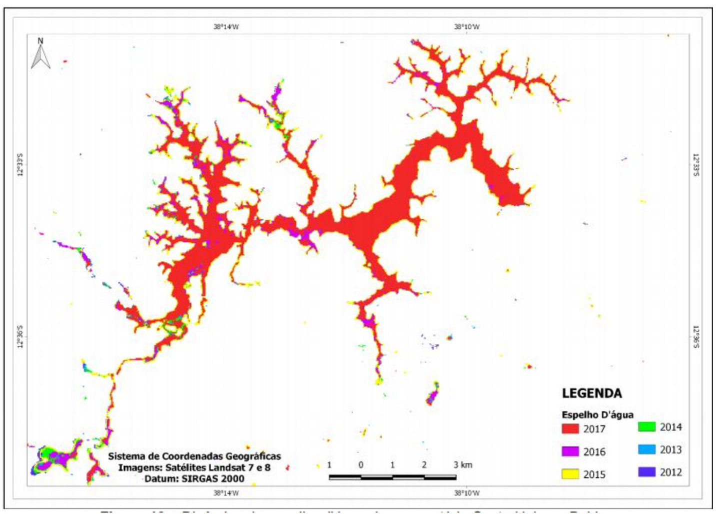

Figure 13. Dynamics of the water mirror of the Santa Helena reservoir, Bahia

Source: Research results, 2022

However, it should be noted that no reservoir completely lost its water mirror in the years observed, even those with low water capacity. The graph of average annual rainfall in the Recôncavo Norte basin for the period from 2011 to 2017 (Figure 14) shows the temporal behavior of rainfall and can help to understand the behavior of the gain and loss of water mirror area in the reservoirs observed.

On the other hand, it should be noted that not all of the basins studied showed losses in area. Contrary to what was observed in other basins, the reservoirs in the Vaza-Barris basin showed a greater increase in water mirror than in 2012, the base year for mapping, as can be seen in Table 6.

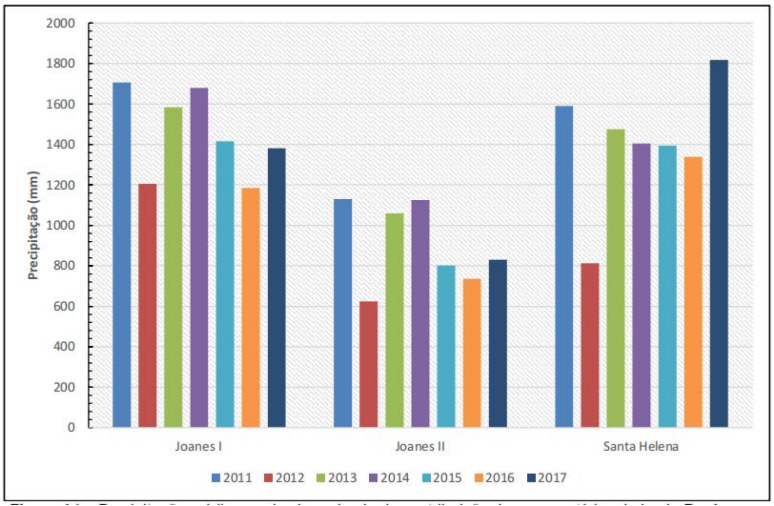

Figure 14. Average annual rainfall over the reservoir contribution basin of the Recôncavo Norte basin for the period 2011 to 2017

Source: adapted from ANA, 2022

Table 6. Temporal variation in the water mirror areas of the reservoirs in the Vaza-Barris basin

Reservoirs	Capacity (m³)	Water mirror areas (Km²)						Percentage change in area: (+) Gain and (-) Loss
		2012	2013	2014	2015	2016	2017	
Cocorobó	245.376.000	10,41	4,41	11,35	7,80	17,95	12,53	+ 20,37
Gasparino	48.607.945	0,02	1,11	1,86	1,85	2,79	2,42	+ 12.000,00

Source: Authors

The gains in flooded area observed in these reservoirs revealed a different behavior from what was seen for all the other basins, since they showed losses and had their areas reduced. Thus, the Cocorobó dam (Figure 15) showed an area gain of just over 20%.

The Gasparino dam, on the other hand, showed a much more significant gain in its flooded area, with a 12,000% increase in its area compared to the base year of 2012. This episode is related to the recent construction of this reservoir, which was completed in 2012. As a result, there was not enough time for Gasparino to reach the full potential of its water capacity.

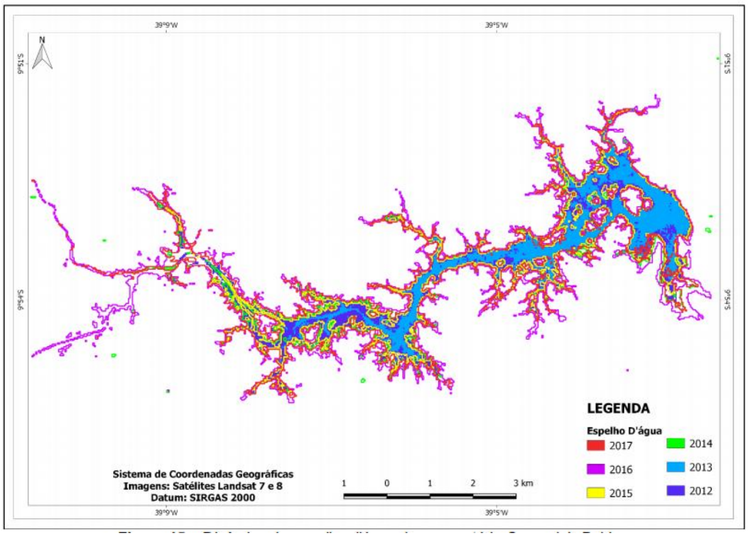

Figure 15. Dynamics of the water mirror of the Cocorobó reservoir, Bahia

Source: Research results, 2022

Unlike the other reservoirs, which managed to convert the accumulated rainfall in 2011 into a volume of water in the reservoirs, as can be seen in the graph of average annual rainfall over the catchment area of the reservoirs in the Vaza-Barris basin for the period from 2011 to 2017 (Figure 16).

In the general context of the increase in the water mirror, the Itapebi reservoir, the only dam mapped in the Jequitinhonha basin, should be highlighted (Table 7). The reservoir showed a gradual increase in area until 2016 and, overall, saw a 7% increase in its area compared to the base year of 2012.

The graph of average annual rainfall for the period 2011 to 2017 over the Itapebi Reservoir catchment area (Figure 17) shows the temporal behavior of rainfall and helps to understand the dynamics of the reservoir's water mirror. The figure shows variability and a downward trend in precipitation values with reference to the year 2013, despite the growth shown by the Itapebi reservoir (Figure 18).

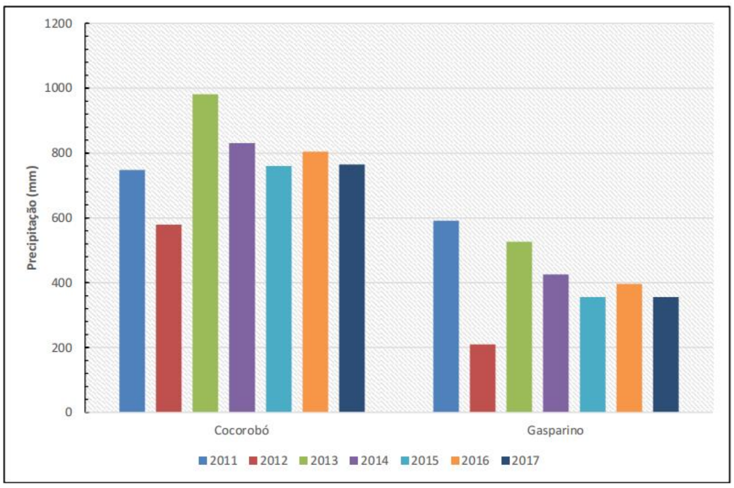

Figure 16. Average annual rainfall over the catchment area of the reservoirs in the Vaza-Barris basin from 2011 to 2017

Source: adapted from ANA, 2022

Table 7. Temporal variation in the areas of the water mirrors of the reservoirs in the Jequitinhonha basin

	Capacity (m³)	Water mirror areas (Km²)	Percentage change in area:

Reservoirs		2012	2013	2014	2015	2016	2017	(+) Gain and (-) Loss
Itapebi	1.633.560.000	50,07	50,78	53,28	51,14	54,17	53,82	+ 7,49

Source: Authors

The graph of average annual rainfall for the period 2011 to 2017 over the Itapebi Reservoir catchment (Figure 17) shows the temporal behavior of rainfall and helps to understand the dynamics of the reservoir's water mirror. In the figure it is possible to see a variability and downward trend in precipitation values with reference to the year 2013, despite the growth shown by the Itapebi reservoir (Figure 18).

This dynamic may be associated with multiple factors, ranging from rainfall concentrated in the sub-basins of this reservoir that was not recorded by the rainfall stations or even changes in water use demands.

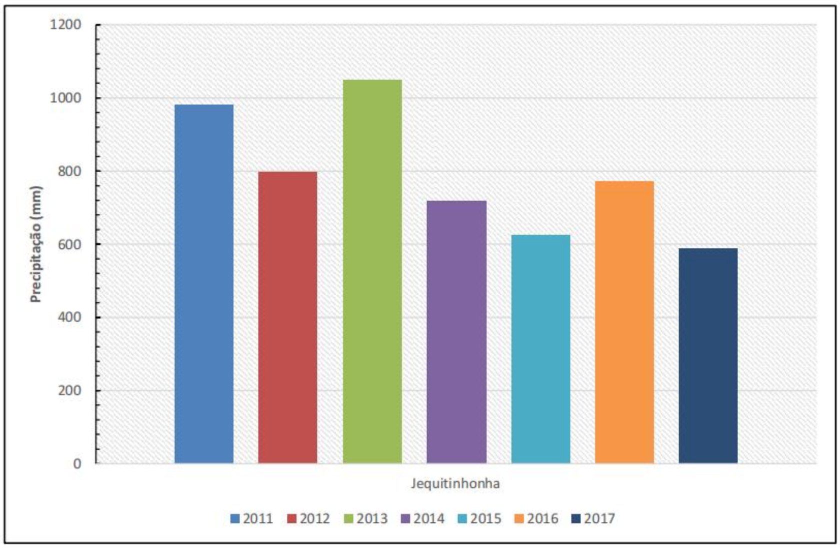

Figure 17. Average annual rainfall over the Itapebi reservoir catchment area in the Jequitinhonha basin for the period 2011 to 2017

Source: adapted from ANA, 2022

The dynamics of the expansion and reduction of water bodies were related in this study as a direct consequence of precipitation events, whether above or below average. However, the sum of climate aspects (evapotranspiration, insolation, sea level, altitude, etc.), as well as hydrogeological and hydrological characteristics, the size of the drainage areas in each basin and multiple forms of use (agriculture, fish farming, electricity generation, etc.), may also have contributed directly to the scenarios presented.

In addition, operational flow control measures for electricity generation, preventive actions to ensure dam safety, water allocation, use restrictions, rationing or even water transposition (PEREIRA et al., 2019), have a direct effect on surface water reserves.

Given the aspects presented above, as well as the environmental diversity of Bahia, it is very complex to pinpoint a single factor responsible for the dynamics of the gain and loss of water mirror area. However, by analyzing only the temporal variability of the precipitation values observed in the graphs, they can be understood as one of the main reasons, as suggested by Medeiros et al(2021), who observed that, although compared to climatological data, the reservoirs in the northeastern coastal areas of Brazil mainly experience negative precipitation, which was not sufficient to culminate in a hydrological drought, unlike the reservoirs in the semi-arid region which, due to the persistence and severity of the negative rainfall anomalies, showing a constant drop in stored volume until they reached a critical situation (MEDEIROS et al. , 2021).

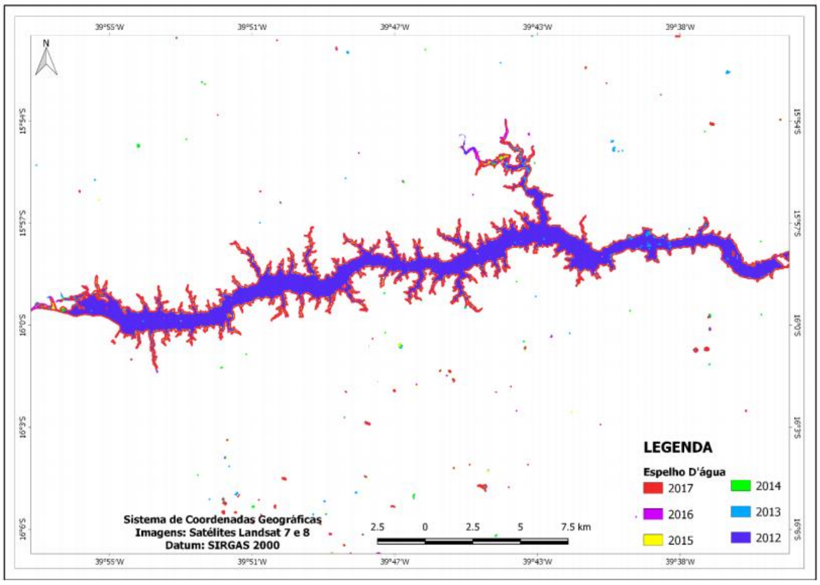

Figure 18. Dynamics of the water mirror of the Itapebi reservoir, Bahia Source: Research results, 2022

As far as methodological procedures are concerned, the same methodology was applied in recent research to analyze the dynamics of water surfaces in the main reservoirs in Rio Grande do Norte (BARBOSA et al., 2019a), Paraíba (BARBOSA et al., 2019b), Ceará (BARBOSA et al., 2021, in press) and Pernambuco (BARBOSA et al., 2022, in press), 2021) and Pernambuco (BARBOSA et al., 2022, in press), where they also pointed out a significant variation in water surfaces between the years 2012 and 2017, i.e. the dynamics of gain and loss of water surfaces in the reservoirs of these states over the same period.

Although the method used to identify the water mirrors in this study is relatively simple and easy to operate, in general terms, the information on the dynamics of the water mirrors found in this study corroborates the mapping data of the water surfaces of the reservoirs in Bahia, available on the internet (https://plataforma. brasil.mapbiomas.org/agua) by the MapBiomas Project - Mapping the Water Surface of Brazil, which uses a much more robust method (https://mapbiomas.org/metodo-agua), where the aim is to provide monthly and annual data on the surface water dynamics of water bodies for the whole country since 1985, and to discriminate between natural and man-made water bodies.

With regard to the limitations and possible shortcomings of the method used, as well as those of remote sensing techniques, some concern the accuracy of adjusting the correct threshold between the spectral signatures of the water table and the wet areas, with or without vegetation, for all the water surfaces in a region as vast and environmentally diverse as the state of Bahia.

In this context, other limitations are well known in the literature when mapping water surfaces over large areas using remote sensing techniques. Krause et al (2021), when mapping the dynamics of water bodies in Australia using Landsat, described limitations such as: incorrect classification of water in deep shadows, shadows of steep terrain, omission of very turbid or colored water bodies, water bodies with a lot of vegetation around them, in addition to spatial resolution limitations.

5 Final considerations

The analysis of spatio-temporal dynamics using remote sensing techniques proved relevant to understanding how the reservoirs reacted to variations in precipitation. The changes pointed out in the dynamics of surface water, both at reservoir level and at basin level in geographically distinct contexts, showed how reservoir waters were affected during the period from 2012 to 2017.

In general, the influence of rainfall variability and the impact of other factors reduced the amount of surface water available, so that of the 34 reservoirs studied, 16 had their area reduced at the end of the period analyzed: Apertado, Araci, Delmiro Golveia IV, Itaparica, Joanes I, Joanes II, Luiz Vieira, Moxotó, Pedra do Cavalo, Pedras Altas, Pindobaçu, Ponto Novo, Santa Helena, São José do Jacuípe, Sobradinho and Zabumbão. Of this amount, five reservoirs are located in the São Francisco basin, four in the Itapicuru basin, three in the Paraguaçu basin, three in the Recôncavo Norte basin and one in the Contas basin.

Given the large number of reservoirs in Bahia, the use of satellite images is an excellent tool for observing, mapping and analyzing the dynamics of water bodies, as well as for measuring the effects of rainfall on reservoirs that supply millions of people, control floods, perennialize stretches of intermittent rivers, store water for hydroelectric power production and foster the economy and irrigated agriculture.

The results of this work can be put to various potential uses in supply policies and planning, helping with decision-making, water management and sustainable use. This information is extremely important for the planning and environmental management of water resources, with a view to promoting supply policies and thereby increasing the capacity to tackle problems related to water security.

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