Heliyon 9 (2023) e12640

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

50 years of the water-flow variance in Tucuruí reservoir related with Brazilian energy consumption

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ARTICLE INFO

Keywords:
Amazonian river
ANEEL
Time-series
ARMA

ABSTRACT

Dammed rivers lose its natural characteristics of the flow cycle and becomes controlled by the energy demands of the hydroelectric plants. With the connection of the energy-producing plants to a central station in Brazil the situation is aggravated since demands in different regions of the country affect the water flow. Using downstream flow data from the Tucuruí dam over a 50-year period, we tested whether the variation in water flow has changed. We observed an increase of the annual variation of the water flow and the extreme events of flooding at downstream of the dam, indicating the operation of the dam intensified the control of water passage. The study reveals an increase in the variation of water flow in the dam's downstream section following the interconnection of the Tucurui dam with the Central System in 1997. Management strategies for the dam should be considered integrated with the national electricity demand, since distant demands may affect the local environment in question.

1. Introduction

Brazil has chosen as a public policy to use hydroelectric power plants as a source for its energy matrix [1]. As the country has a relatively large territorial extension and population size, the demand for construction of the plants has been intensified over the years [2,3]. Some power plants that have already been built, and others that are still under construction, are large-scale developments, making it possible to use large rivers to generate a massive amount of electricity. Consequently, these large plants generate water reservoirs of large territorial extension, through the process of flooding the region upstream of the dam [4]. Many studies already point out modifications in hydrological, environmental, biological, and social dynamics in upstream reservoirs [5], since there is a modification of the system that previously had a flowing water dynamic (lotic) to a still water system (lentic). One element that has increasingly gained considerable attention in this electric power production system is how the dams may be altering the water dynamics in the regions after (downstream) the dam [6].

Once a dam is built and begins operation, the natural dynamics of filling and flowing of the river, which follow the rainfall cycle of the watershed region, are replaced by the control of water flow needed for power production. As a result, the region downstream of dams can exhibit drastic changes in its flow regime [7]. An example of this change is the observation of cycles of expected flow changes over long time periods (seasons) occurring at very short intervals (days or weeks). Changes in these flow cycles have repercussions on local human populations, such as changes in demand for the water resource, and also on the ecosystems associated with the water

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https://doi.org/10.1016/j.heliyon.2022.e12640
Received 13 July 2022; Received in revised form 30 September 2022; Accepted 19 December 2022

body.

The main changes in ecosystems are related to the species population dynamics, since these organisms have bionomic characteristics that are adjustable to the cycles of these environments [8–10]. A clear example is the use of river floodplains, which have a filling and emptying periodicity that accompanies the rainy season, for egg deposition, turning them a favorable breeding site. The control of water flow coming from the dam can make it difficult for species, especially fish, to find suitable sites for their reproduction during fertile periods, or even an action of eggs being dragged by the current when the canal emptying occurs. On the other hand, during the flood period, the water column in the floodplain presents a dynamic similar to lentic systems, which facilitates the deposition of nutrients that were suspended in the water column onto the substrate [11]. Without the possibility of the water remaining for a longer period of time in the floodplain, due to the prolonged period of flooding in the river, the amount of nutrients that sediment tends to decay, thus reducing the productivity in these environments.

The water flow of a dammed river then starts to respond to the electric power demands of the consumer units that are connected to the power plant. Brazil has been adopting the policy of interlinking its electric power grid (Resolution 351 of November 11, 1998), in such a way that the production plants supply the entire power grid of the country. In addition, the country has been experiencing an increase in the per capita consumption of electricity with the advent of new technologies more accessible to the population, expansion of the national industrial matrix, and the incentive to increasing the distribution network, which puts increasing pressure on electric power producers [12].

As a consequence, the control of river flow is no longer local, but on a country-wide scale, since at any moment, the national power matrix can demand a greater production to serve regions that are far from the plant. The effect of the interconnection between energy production units has an amplified effect, since the national production of electricity through hydroelectric plants has increased from 50 TWh (Tera Watts Hour) in 1970 to approximately 620 TWh in 2018 (an increase close to 1240%) [13]. As there is a direct relationship of the increase in turbine volume to the energy production by a hydropower plant [14] the pressure for energy demand at a plant increases its water footprint, more drastically altering the water regime by forcing ecosystems into new environmental conditions.

The Tucuruí hydroelectric dam is located on the Tocantins River in the Amazon region and is one of the largest plants in operation in Brazil. Since its construction and subsequent operation, the flow of water has been controlled, authorizing the so-called ecological flow, which directly affected many ecological processes of the river (migration of species and flow of energy and matter, e.g.). The dam was joined to the National Interconnected System (SIN) in 1997, and from that moment on the control of energy production became the responsibility of the National Electric System Operator - ONS. Our study tested if after the interconnection of the hydroelectric plant to the SIN there were any changes in the variation of water flow in the downstream part of the dam. In addition, we also tested whether extreme hydrological events (high flows and/or floods) in the downstream part of the dam increased in frequency, generating greater environmental and social stress.

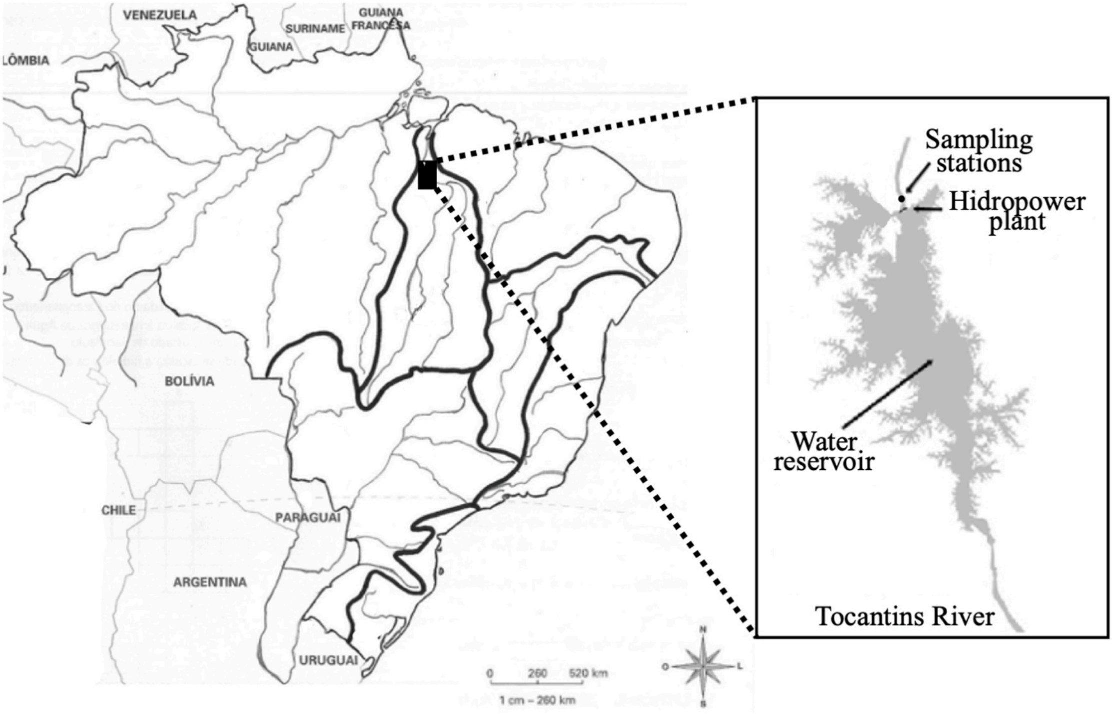

Fig. 1. Tucuruí Hydroelectric Reservoir and the location of sampling points.

2. Methods

2.1. Area of study

The Tocantins River basin presents a large water catchment area, draining a total area of 767,000 km^2 and is inserted in a region of hot and humid tropical climate [15]. The seasons of the year are divided in less rainy and rainy periods, with the dry season between the months of September and October, and the season considered high water, around February to April. In the rainy periods, which start around November and December, precipitation averages 300 mm, reaching 1–50 mm in the less rainy season. Extensive rocky or sandy islands and beaches are found along the banks of the Tocantins River, which appear in the dry season in its middle course, while in the lower course of the river, alluvial islands are predominant. Floodplain lakes are uncommon, but appear in the floodplains in its upper course at the Tocantins-Araguaia confluence, and in the lower course below the town of Tucuruí [16].

2.2. Data acquisition

The water flow data for the downstream part of the Tucuruí Hydro Power Complex were obtained from two different sampling stations, but with a proximity of 1 km between them (Fig. 1). It was necessary to use the two stations because the records from both stations are complementary in the time series, since one of the stations was deactivated when the other started its operation. In the period from 1970 to 1998 the flow was measured by the station under the responsibility of the National Water Agency (3°45′28.08″ S and 49°39′11.88″ W). For the period from 1999 to 2017, the measurement was obtained by the station under the responsibility of Eletronorte/Eletrobrás (3°46′45.12″ S and 49°39′29.88″ W). Both stations' data were accessed via the official publication channels for this information [17,18]. Considering that the stations do daily measurement of water flow, measured in m^{3}s^{-1}, the historical series we dealt with was from January 1, 1970 to December 31, 2017. As a way to ensure the accuracy and quality of the data, we observed possible gaps in the database and estimated possible discrepant values. Such results were not found in the original database, indicating adequate reliability for the data analyses.

2.3. Data analysis

We used an autoregressive moving average (ARMA) model to remove the effect of temporal autocorrelation for the daily downstream flow observations at the Tucuruí dam. In this model that the moving average was estimated using the previous and subsequent two days, and the autocorrelation was estimated using the previous day's flow observation (we employed values of 2 and 1 for the ARMA parameters). ARMA analyses are relevant in time-series studies, as they allow the isolation of time trend effects, such as the natural variability of seasons, from point effects that occur during the observed period. Because of these characteristics ARMA models are suitable for temporal analysis, as the residual values of their estimates are related to effects other than temporal autocorrelation effects.

We used the estimated daily values from the ARMA model to determine the annual variation of the flow rate from what is expected. For this estimate, we used the root mean square (OLS$^{1/2}$) for the difference between the observed and expected daily values. The OLS$^{1/2}$ is estimated by equation (1), in which, y_i the flow value on day i, $\widehat{y}_i$ the estimated flow value by the ARMA model for day i, and n the number of days in the year.

$$OLS^{1/2} = \sqrt{\frac{(y_i - \widehat{y}_i)^2}{n}} \quad (1)$$

With the estimated annual OLS$^{1/2}$ values, we used a segmented linear regression to test whether there was a trend of change in downstream flow over the years, as well as possible changes in trends.

To characterize the daily variation in flow we calculated the differences between subsequent days of the observed values. In this way we could observe if in a 24-h period there were very abrupt changes in the flow downstream of the hydroelectric plant. We

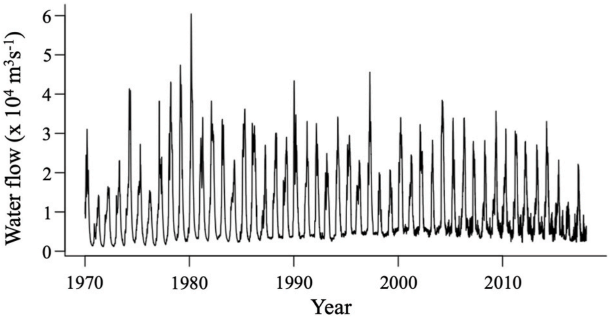

Fig. 2. Time series of daily values predicted by the ARMA (2,1) model for the downstream flow of the Tucuruí dam from 1970 to 2017.

separated out the values of greatest daily variation in flow, both increase and decrease, for each year in the time series. This value indicates the extreme events, in which the flow varies greatly, and was used in this study to characterize drastic variations in water flow. With these values, we tested whether there was a temporal trend using two segmented linear regressions, both for the extreme annual upstream and downstream events.

3. Results

The time series predicted by the ARMA model for the daily flow rate from the downstream part of the Tucuruí dam showed 17,532 observations (average of 10,411.89 m^3s^{-1} ± 8772.06 m^3s^{-1}, with a minimum of 1155.19 m^3s^{-1} and a maximum of 60,438.65 m^3s^{-1}). The highest values of flow were in the year 1980, when the rivers of the region presented an abnormal elevation of their water volume caused by the precipitations at the end of 1979 and beginning of 1980. After this period, the maximum and minimum values remained constant within the annual periods (Fig. 2).

The annual variation of the downstream flow had a tendency to increase over the years (Table 1). In 1997 there was an acceleration in this increase of annual variation, indicating that from this year on, the events of daily alteration of the flow were greater than would be expected by the autoregressive model (Fig. 3). This deviation indicates that these observed changes present a greater magnitude of change, resulting from drastic variations in the observed flow values.

Besides the increase in the annual variation of the flow with the passage of time, the daily differences also had the tendency to increase with the passage of the years (Fig. 4). Starting in the year 2000, the daily differences tended to increase, and the increase was continuous until the end of the time series. From 2010 onward, the high variation events tended to be almost daily, leaving the region downstream of the dam with cycles of high and low water level completely different from what would be expected from the natural dynamics of the river.

The increase in variability in the daily flow was accompanied by a tendency to increase the daily extreme values (Table 2, Fig. 5). The values of extreme differences of each year increased linearly and had a moment of acceleration from the year 2000. This result indicates that besides the occurrence of greater daily variability in water flow, the downstream part of the dam had an increase in the occurrence of extreme events, with very accelerated high and low water level.

4. Discussion

The water flow in the region downstream of the Tucuruí dam showed an increase in its variability over the years, with this increase being accompanied by a greater number of extreme events of flooding and flow of the river (over short periods of time, caused by the operation of the dam). This situation worsened from 1997 to 2000, a period in which there was an acceleration in the tendency to increase. This result shows that the river's natural flood cycle is gradually being superseded by a periodicity related to power plant energy production. This periodicity, in turn, would have a much shorter frequency, where peak flows can have intervals of up to one day. Such a replacement of the cycle is something that has already been documented for other hydropower plants in various regions of the world, showing that the river's natural flood cycle is gradually being replaced by a periodicity related to power plant energy production, and has direct responses on both the biological communities and the human populations living along the river banks [7].

A relevant and differential point in our study relates to the governmental dynamics that Brazil has been employing for energy production. The interconnection of the Tucuruí power plant to the SIN in 1997 appears to be a landmark in the trends observed in our results. As of this year, the divergence of the flow dynamics from what would be expected in a natural environment accelerates, maintaining a very high rate of change. In addition, as energy demands become greater and greater, as the power plant begins to serve a larger distribution network, energy production undergoes moments of greater intensity, which leads to the release of a greater volume of water. At the end of this process, increased demand-increased production-greater release of water volume, the externality is for the downstream part of the river that suffers large flooding events at a very fast rate, accompanied by rapid receding.

The use of natural resources has always been accompanied by externalities events, either directly or indirectly [4]. There is a vast literature that demonstrates the local effects that human modifications generate to natural systems, and also for traditional populations [19–21]. High impact actions are normally expected to have effects, usually negative, in a short period of time and limited spatial range [21]. However, several current contexts concerning the means of production, distribution and consumption by human societies have widened the scope of impacts. We can highlight that the current major concern of the scientific and governmental community is related to the effects of human action on global climate change [22]. The scenario reported in our study falls within this context, in which the actions of human populations create adverse conditions in very remote regions.

The new reality of the downstream stretch of the Tocantins River after the Tucuruí dam is a deleterious environment for the biological communities living in the river canal, particularly fish and crustaceans, as well as for the riverside populations living along its banks that depend on fishing resources. When the river level rises too rapidly, many organisms tend to move to the margin regions

Table 1
Effect of the year on the increase in flow variation ($OLS^{1/2}$).

Coefficient	Estimated	Standard Error	T	P
Intercept	−20,419.32	4838.70	−4.22	<0.01
Year	10.44	2.44	4.28	<0.01
Year after 1997	37.41	4.72	7.92	<0.01

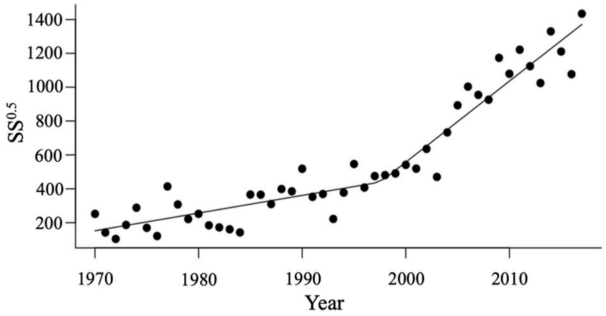

Fig. 3. Increase in the variation of the downstream flow of the Tucuruí dam between the years 1970 and 2017. In 1997 there was a change in the regression coefficients of the model, generating a break in the trend and accelerating the increase in variability.

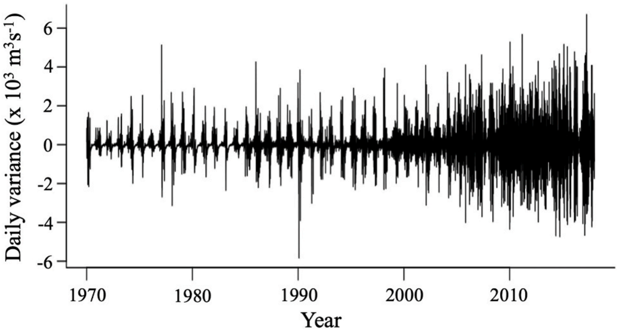

Fig. 4. Daily differences in water flow downstream of the Tucuruí dam. Positive values indicate the flow increase in subsequent days, while negative values would indicate a reduction in the flow.

Table 2
Effect of the year for the increase in extreme events of variation in water flow.

Coefficient	Estimated	Standard Error	T	P
Intercept	−62,186.36	35,172.56	−1.80	0.08
Year	35.21	17.19	2.05	0.04
Year after 2000	127.44	47.14	2.70	0.01

The estimate for year after 2000 is for the model after the regression breaking point, estimated at 2000.99 with a standard error of 4.10. The adjusted R2 for the model was 0.56.

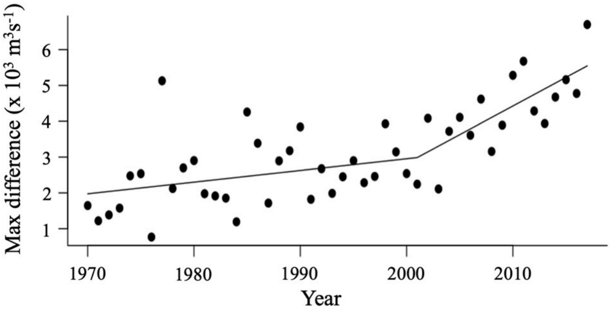

Fig. 5. Increase in extreme event values of the variation in the downstream flow rate of the Tucuruí dam between the years 1970 and 2017. In 2000 there was a change in the model regression coefficients, generating a break in the trend with an acceleration in the increase in extreme values.

(floodplains). When it is no longer necessary for the turbines to raise the water level for energy production, the affluent flow in the dam is again reduced, which leads to an accelerated low level water event in the downstream part of the river. At this point the river reduces its water column to the levels considered normal for the operation of the power plant, and the entire floodplain region, previously flooded, quickly dries up. Consequently, with this accelerated withdrawal of water from the floodplain, many organisms that have moved into this environment end up being trapped in temporary pools, which usually dry out quickly, thus generating a high mortality of fish and crustaceans.

Many riverine populations have pointed out this problem of animal mortality due to sudden changes in the flow downstream of the dam. Despite the fact that riverbank dwellers have reported the high mortality rate and documented it in videos (see video https://doi.org/10.5281/zenodo.6539935), no study has yet been established to estimate the biomass and number of dead animals. Even without these numerical estimates, we see that this value can be very high according to the documents presented by the local people. Most of the animals that die in this process of rapid filling followed by a rapid runoff are species of economic and sustainability value for these riverbank populations. The loss of these organisms can then be seen as having both an environmental impact (loss of species) and a socioeconomic impact (loss of vital resources to traditional populations).

The future outlook for the region downstream of the Tucuruí dam tends towards a scenario where the alterations in the dynamics of the flooding and runoff tide of the river will aggravate. In recent years, Brazil has faced successive water crises, where the shortage of rainfall in the South and Southeast regions has reduced the reservoir levels of the main hydroelectric plants in these regions [23]. We can report that the main factors related to this increase in rainfall deficit are the increase in deforestation in Brazil, especially in the Amazon region, and global climate change [24,25]. With the low power generation capacity of these plants close to industrial centers and large cities, the need for more distant plants to supply this energy demand is increasing. Since the Tucuruí HPP has one of the largest water reservoirs in the world, this hydropower plant is a strategic resource, since its production capacity is capable of meeting greater demands. From this point of view, we can speculate that the tendency is for a steady increase in downstream flow variability, as well as the increase in extreme cases of variation in the height of the river's water column.

The results of our study indicate a need for greater participation of local populations for control and decisions about the management of water flow in the reservoirs. Measures such as advance warning to these populations about possible events of major floodgate opening, which would lead to a large filling of the downstream part of the river, may be desirable, but are not enough to minimize environmental damage. The warning would make it possible decision making that would minimize the deleterious effects that these rapid floods have on fish stocks, thus preventing the mortality of these animals from being wasted. In addition, for the governmental decision-making sphere, it would be preponderant that the energy demands coming from the national integrated system did not overload only one generating unit. It is necessary to have a governance of the energy system in which there is an integrated vision with the local and regional socioenvironmental issues where the hydroelectric plants are located, especially in the Amazon region. In such a region there must be a greater concern with its sustainability that is so important for the planet. To this purpose, the establishment of a system-wide strategy of diffuse demand will make it possible for these events of intense energy production by the hydroelectric plants to have a less steep production acceleration curve (and thus reduce the speed of floodgate opening), since a large number of plants would be feeding the demand. Another mechanism that can cushion the effects of flow control in large rivers, especially during the dry season, is an increased use of solar energy, thus setting up a hybrid system of energy production and distribution [26]. Such measures would enable a large reduction in the impacts that long-distance activities would have on traditional populations and environments where electricity is generated.

5. Conclusion

Visualizing the downstream effects of dams is essential to identify, control, and minimize the impacts of changing the water regime of large rivers. Very drastic changes in this regime can lead to loss of useable areas, through unstable flooding regime, as well as increased mortality of aquatic organisms such as fish and crustaceans. Despite the pattern of alteration in the hydrological dynamics of the Tocantis River, we emphasize that additional studies are necessary to identify if the loss of riparian forest in the river basin can influence this change in the river's hydrological regime. We emphasize that with the advent of tools that increasingly connect distant regions, we may have to replace the maxim “think globally and act locally” with “think globally and act globally too."

Authors contributions

Godoy BS analyzed the data, discussed the results, and wrote the manuscript. Ishihara JH discussed the results and revised the article. Aguiar RL collected and organized the data. Teixeira ON conceived and designed the experiment and reviewed the article.

Data available Statement

Data available at Zenodo in: https://doi.org/10.5281/zenodo.6667609

The estimate for year after 1997 is for the model after the regression breakpoint, estimated at 1997.55 with a standard error of 1.63. The adjusted R^2 for the model was 0.92.

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