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THE LOWER RIVER SOLIMÕES FROM THE PERSPECTIVE OF CHAOS THEORY (DETERMINISTIC CHAOS)

O baixo Rio Solimões pela Perspectiva da Teoria do Caos (Caos Determinístico)

El Bajo Río Solimões Desde La Perspectiva De La Teoría Del Caos (Caos Determinista)

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SUMMARY

The study of non-linear dynamic systems has been receiving more and more attention from the scientific community. Chaos Theory, developed in the early 1960s, seeks solutions for systems that do not approach equilibrium or a periodic solution, thus discovering chaotic motion (oscillations irregular and aperiodic) on a strange attractor. This discovery was a breakthrough for the analysis of hydrological dynamics, now considered a non-linear system. Therefore, this article seeks to present, from the perspective of Chaos Theory, potentialities for the hydrological analysis of a river system. For this, we analyzed if the fluvial dynamics and erosion and sedimentation processes, in addition to understanding data on quotas, liquid discharge and suspended sediments, seeking to understand the monthly averages to predict the data from the perspective of Chaos Theory. The results indicate that the analysis of turbulent flows, in particular, helical flows, and sediment transport and deposition processes is interesting from the Chaos perspective for a short time scale, being difficult to predict the results on a longer time scale. The use of monthly averages to predict phenomena given by quotas, liquid discharge and suspended sediments is not indicated by the non-linear dynamics of the data, however it is possible to predict the data in a short temporal scale. It was also observed that the greater the predicted time scale,

Key words: Non-Linear Analysis; Great Rivers; Amazon Basin; Complexity.

RESUMO

O estudo dos sistemas dinâmicos não-lineares vem recebendo cada vez mais atenção da comunidade científica. A Teoria do Caos, desenvolvida no início da década de 60, busca soluções para sistemas que não se aproximavam do equilíbrio nem de uma solução periódica, descobrindo assim, o movimento caótico (oscilações irregulares e aperiódicas) sobre um atrator estranho. Esta descoberta foi um avanço

para a análise da dinâmica hidrológica, considerada agora um sistema não-linear. Portanto, este artigo busca apresentar, sob a perspectiva da Teoria do Caos,
potencialidades para a análise hidrológica de um sistema fluvial. Para isto, analisou-se a dinâmica fluvial e processos de erosão e sedimentação, além de entender dados de cotas, descarga líquida e sedimentos em suspensão, buscando compreender as médias mensais para prever os dados sob a perspectiva da Teoria do Caos. Os resultados apontam que análise dos fluxos turbulentos, em específico, fluxos helicoidais, e processos de transporte e deposição de sedimentos é interessante sob a perspectiva do Caos para uma escala de tempo curta, sendo difícil prever os resultados em uma escala de tempo maior. A utilização de médias mensais para prever fenômenos dados de cotas, descarga líquida e sedimentos em suspensão não é indicada pela dinâmica não-linear dos dados, porém é possível prever os dados em uma escala temporal curta. Observou-se, também, que quanto maior for a escala temporal prevista, maior a chance de haver inconsistências nos dados, não sendo indicada o uso para previsões, usando a Teoria do Caos, superiores a um ano.

Palavras-chave: Análise Não-Linear; Grandes Rios; Bacia Amazônica; Complexidade.

RESUMEN

El estudio de los sistemas dinámicos no lineales está recibiendo cada vez más atención por parte de la comunidad científica. La teoría del Caos, desarrollada a principios de la década de 1960, busca soluciones para sistemas que no se acercan al equilibrio ni a una solución periódica, descubriendo así el movimiento caótico (oscilaciones irregulares y aperiódicas) sobre un atractor extraño. Este descubrimiento fue un avance para el análisis de la dinámica hidrológica, ahora considerado un sistema no lineal. Por tanto, este artículo busca presentar, desde la perspectiva de la teoría del Caos, las potencialidades para el análisis hidrológico de un sistema fluvial. Para ello, se analizaron la dinámica fluvial y los procesos de erosión y sedimentación, además de comprender datos sobre cuotas, descarga líquida y sedimentos en suspensión, buscando comprender los promedios mensuales para predecir los datos desde la perspectiva de la teoría del Caos. Los resultados muestran que el análisis de los flujos turbulentos, en particular los flujos helicoidales, y los procesos de transporte y deposición de sedimentos, es interesante desde la perspectiva del Caos para una escala de tiempo corta, lo que dificulta predecir los resultados a una escala de tiempo mayor. El uso de promedios mensuales para predecir fenómenos de datos de cuotas, descarga de líquidos y sedimentos en suspensión no está indicado por la dinámica no lineal de los datos, sin embargo, es posible predecir los datos en una escala de tiempo corta. También se observó que cuanto mayor es la escala de tiempo predicha, mayor es la posibilidad de inconsistencias en los datos, y no se indica el uso para predicciones, utilizando la teoría del Caos, mayor de un año.

Palabras-clave: Análisis no lineal; Grandes Ríos; Cuenca del Amazonas; Complejidad.

1 INTRODUCTION

During the second half of the 20th century and the beginning of the 21st century, there was a great interest of the scientific community in the development of non-linear phenomena (HAKEN, 1982), resulting in the introduction of new concepts and approaches in the treatment of dynamical systems: conservative and dissipative.

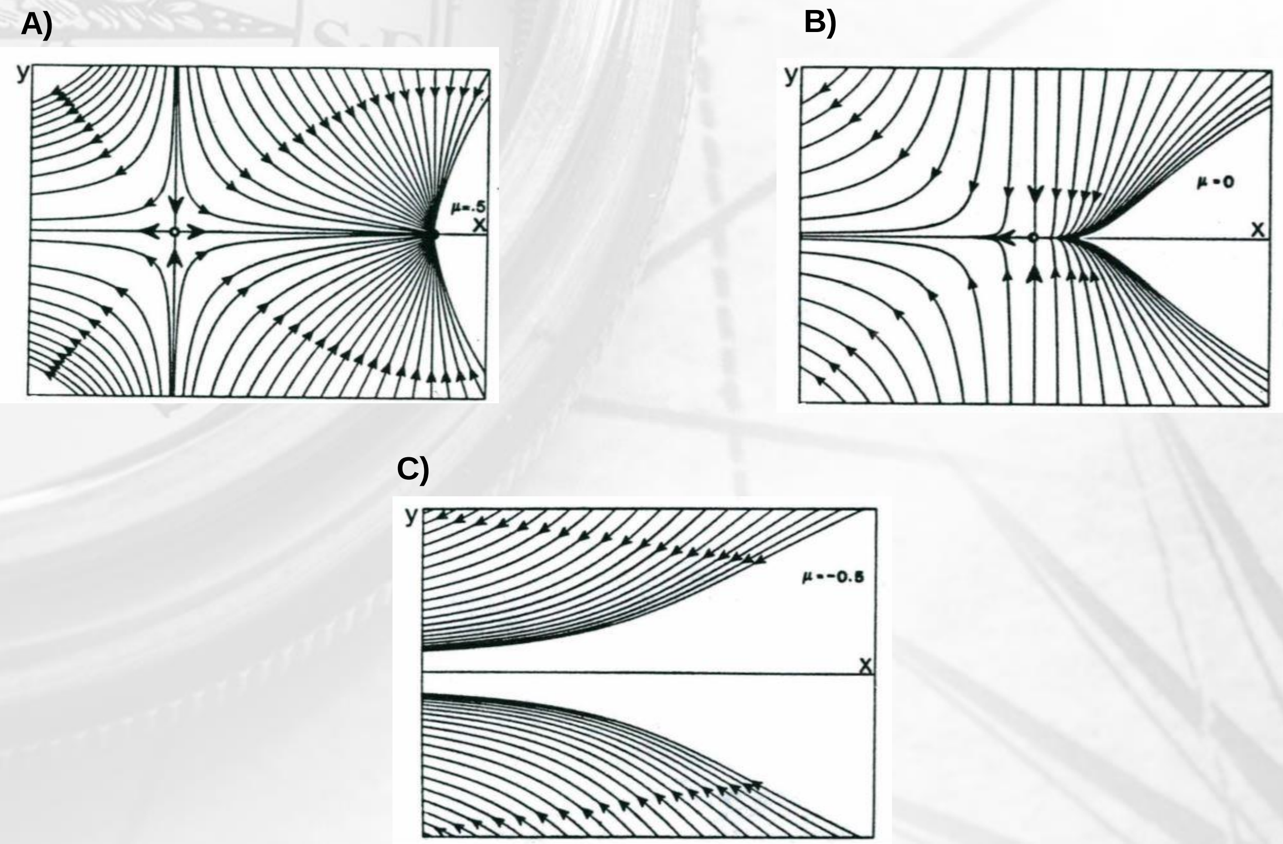
The tradition of studying dynamic systems dates back to Henri-Poicaré (1814-1912), who realized the usefulness of topological analysis in the phase space of dynamic trajectories inspired by problems in Celestial Mechanics (more details in POICARÉ, 1899).

With CD Birkhoof's important contributions to Ergodic Theory and foundations of statistical mechanics, strengthening Poincaré's theoretical bases, the science of non-linear, based on non-linear dynamics, enriches the pre-existing view of Classical Physics (FIEDLER-FERRARA; PRADO, 1994).

Non-linear dynamics is the study of the evolution of non-linear systems, and the relationship between cause and effect is not proportional and determined, but rather vague and difficult to discern. These systems can be characterized by the interaction between non-linear and linear variables over space-time, that is, the phenomenon can present linear characteristics at a given moment, but the relationships between the variables can change causing drastic alterations that are called bifurcations (SIVAKUMAR, 2017).

The bifurcations can be understood as the qualitative variation in the nature of a dynamic system when there is variation in one of the analyzed parameters, where new stationary points can appear and others that were previously stable cease to be and vice versa (Figures 01 a, b, c) (FIEDLER-FERRARA; PRADO, 1994; MORENO, 1997). The concept of Chaos in non-linear dynamical systems is always linked to bifurcations of some kind.

Figure 01 – Examples of Saddle-Node bifurcation (phase diagram, A, B, C).



The figures represent a 2nd order dynamical system. The system has two hyperbolic equilibrium points: a node and an arrow. As the system approaches the bifurcation value μ0, these two equilibrium points approach, resulting in a collision for μ=μ0. If the system continues to vary μ in the same direction, there is no longer an equilibrium point in the neighborhood.
Source: Moreno (1997).

Manipulation through advances in the computation of non-linear systems, allowing the handling of formulas with a certain degree of complexity, led Lorenz (1963) to note, based on a meteorological model, that the solutions of a system did not approach equilibrium. nor a periodic solution, thus discovering chaotic motion (irregular and aperiodic oscillations) on a strange attractor. This new science of complexity, throughout the second half of the 20th century, proved to be applicable to several areas: meteorology, physics, chemistry, biology, social and human sciences, engineering, among others.

Chaos Theory brought several implications to the Newtonian paradigm, which is based on predictability, order and stability. However, Chaos is based on non-linearity, disorder and instability, based on the principle of uncertainty. According to Prigogine (1993), the notion of unpredictability of Chaos is based on probabilistic and irreversible concepts, that is, it is possible to trace a “path” for phenomena based on probability, focusing on the number of variables analyzed (within the system).

Although non-linearity means that changes in system inputs will not necessarily cause proportional changes in outputs, this does not indicate that there is a complete absence of determinism/predictability, now represented by the principles of probability. In reality, nonlinearity tends to have inherent determinism on the one hand and be sensitively dependent on initial conditions on the other. While the first allows the prediction of short-term events, the second eliminates the C) possibility of accurate long-term prediction. This class of non-linearity is known as “Deterministic Chaos” (SIVAKUMAR, 2017).

This new perspective brought many advances to the analysis of geomorphological systems, which in the context of the research could be analyzed from the perspective of non-linearity, bringing greater complexity to the proposed models. Therefore, this article seeks to present, from the perspective of Chaos Theory, potentialities for the hydrological analysis of a river system.

2 APPLICABILITY OF CHAOS THEORY IN HYDROLOGY

The non-linear nature of hydrological systems has been studied since the second half of the 20th century and the beginning of the 21st century, and the hydrological cycle itself presents a non-linear behavior, with almost all the individual components that make up the cycle presenting non-linear behavior. -linear too. A classic example of Chaos in hydrodynamics is the Bénard instability. This experience consists Prigogine (1993, p. 22), in:

> Imposition of a vertical temperature gradient to a horizontal fluid stratum, until the temperature difference between the lower surface and the upper surface of the stratum becomes quite large; at this point, eddies form in the liquid, in which billions of particles run vertiginously one after the other, creating characteristic hexagonal-shaped structures.

This chaotic situation creates different long-term correlations, such as the very organization of the particles in the formed vortex. This non-equilibrium phenomenon clearly demonstrates the notion of irreversible phenomena. In hydrology, this experiment can be seen applied to the natural turbulent movement of river water.

With the experience of Bénard, several methods of analysis using deterministic Chaos have spread in hydrology, since areas include precipitation, river flow, precipitation-runoff, sediment transport, transport of groundwater contaminants, modeling, forecasting , noise reduction, dimensioning, disaggregation, estimation of missing data, reconstruction of system equations, estimation of parameters and classification of watersheds, among others. (SIVAKUMAR, 2017) (Chart 01)

Chart 01 – Application of Chaos Theory in Hydrology.

Data	References
Precipitation	Hense (1987); Rodriguez-Iturbe et al. (1989); Sharifi et al. (1990); Tsonis et al. (1993); Sivakumar (2000, 2001)
river flow	Wilcox et al. (1991); Wang e Gan (1998); Jayawardena e Gurung (2000); Lisi e Villi (2001); Phoon et al. (2002); Zhou et al. (2002); Khatibi et al. (2012); Tongal e Berndtsson (2014)
Sediment Transport	Sivakumar e Jayawardena (2002); Shang et al. (2009)
Groundwater	Sivakumar et al. (2005)

Source: Organization of the authors (2021).

The application of studies in non-linear systems shows three types of temporal behavior: 1) stable (mathematical equilibrium or fixed point); 2) stable, smooth and periodic oscillation between mathematical points; 3) apparently random, devoid of pattern (or non-periodic behavior), dominated by uncertainty and interrupted predictability (SIVAKUMAR, 2017). This can be applied in hydrology for temporal studies of hydrological variables (liquid discharge, suspended sediments, among others). The application of Chaos Theory in recent works (see Chart 01) in hydrology follows concepts of deterministic Chaos that seeks, through the analysis of non-linear equations and probability, to predict apparently random phenomena.

3 STUDY AREA

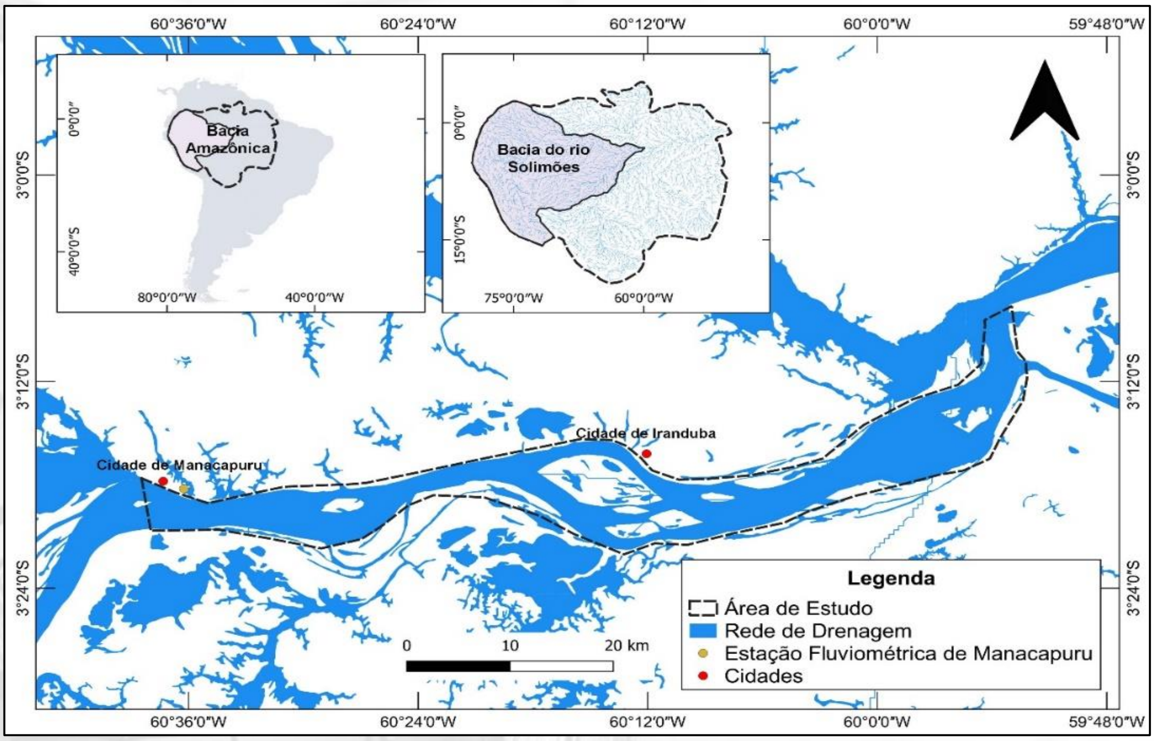
The Solimões river basin has an approximate area of 2.2x106 km2 and drains a variety of geological and geomorphological domains. The Solimões River, the main river in the basin, has its source in Peru and its mouth at the confluence with the Negro River to form the Amazon River.

The last fluviometric reference station on the Solimões River (Manacapuru Station) has an average annual net discharge of 103,000 m3 s-1, the flood peak occurs in June and the ebb in October (VILLAR et al., 2018; QUEIROZ; TOMAZ NETO, 2019). The Amazon River, has an average annual discharge of 209,000 m3 s-1, at the station of Óbidos, in the state of Pará, upstream of the municipality of Santarém, being the largest in the world in this regard (MOLINIER et al., 1996).

The Solimões/Amazonas system is one of the largest river systems in the world, and at the Manacapuru station it has the highest flow in the world (103,000 m3 s-1) (VILLAR et al., 2018), almost twice that of the Congo River in Africa, the second largest in this regard (40,900 m3 s-1) (LATRUBESSE et al., 2005). Latrubesse (2008) considers that rivers with a net discharge greater than 17,000 m3 s-1 can be classified as megarivers, having their own hydrogeomorphological dynamics.

The discharge of sediments from the Solimões/Amazonas River is controlled by the type of soil, slope, climate, geology and morphology of the basin, and, in recent years, anthropogenic activity has started to influence (burning/deforestation, construction of dams, industrial activity, mining, among others) in sediment transport (MERTES et al., 1996; DUNNE et al., 1998; VILLAR et al., 2018). At the Manacapuru station the sediment discharge can be calculated between 400 and 700 Mt yr-1 (DUNNE et al., 1998; FILIZOLA, 1999, 2003; LARAQUE et al., 2005; FILIZOLA; GUYOT, 2009). Given the unique conditions of flow, sediments and the variety of geomorphological features, the area near the mouth of the Solimões River was delimited for analysis from the perspective of Chaos Theory, to which ranges from the city of Manacapuru to the confluence with the Negro River, corresponding to an area of 566.6 km2 (Figure 02).

Figure 02 – Location of the Study Area.



Source: Organization of the authors (2021).

4 MATERIAIS E MÉTODOS

The dynamics of erosion and sediment deposition were analyzed from the perspective of Chaos Theory, identifying the morphological alterations and possible implications for the hydrogeomorphological dynamics of the area. For this, fieldwork was carried out in the study area between the years 2018 and 2020 and four Landsat 8 OLI sensor images provided by the United States Geological Survey - USGS (https://earthexplorer.usgs.gov/) were used to observe the hydrodynamics and understand, through multi-temporal analyzes between 1991 and 2020, how the processes are related to Chaos Theory (Table 01).

Table 01 - Landsat images used.

Satellite	Sensor	Analyzed Bands	Acquisition Date	orbit	Spatial Resolution	Fluviometric Quota (Manacapuru)
Landsat 8	OLI	4, 3, 2 (true color)	12/11/1991 (low water)	Heliosynchronous	30 x 30 m	724 cm
-	-	-	13/11/2003 (low water)	-	-	-
-	-	-	29/11/2009 (low water)	-	-	771 cm
-	-	-	11/11/2020 (low water)	-	-	758 cm

Source: Organization of the authors (2021).

For the analysis of deterministic chaos, the stochastic method was used, which is based on probability and statistics (to predict or estimate phenomena), based on the study of time series. This method can be applied to hydrological studies (HURST, 1951; 1956; HANNAN, 1955; LE CAM, 1961; MANDELBROT; WALLIS, 1968; SIVAKUMAR, 2017; among others). Normally, in hydrology, time scales are related to discrete data analysis (hourly, daily, monthly, annual), such series can be described as (Equation 01):

(01)

$$X_i, i = 1, 2, \dots, N$$

ON is the total duration of observed time and therefore usually represents the total number of data points (or points) in the time series. This work focuses on monthly data on net discharge, suspended sediments and elevations. Made available by the HYBAM project (https://hybam.obs-mip.fr/pt/website-under-development-4/) at Manacapuru station (code = 14100000), the time series corresponds to the data available for each parameter (Table 02):

Table 02 – Analyzed hydrological parameters.

Parameters	Time Series	Number of Data	Station	Source
Liquid Discharge	1973 - 2018	16.620	Manacapuru (14100000)	HYBAM
Sediments in Suspension	1995 - 2014	516	Manacapuru (14100000)	HYBAM
Quotas	1973 - 2018	16.768	Manacapuru (14100000)	HYBAM

Source: Organization of the authors (2021).

Suspended sediment data are available in mg l-1, but for comparison purposes, we chose to use data in ton day-1, for the conversion, Equation 02 was used:

(02)

$$Q_{ss} = 0{,}0864.Q.C$$

The Qss is the sediment load in ton day-1. Q is the net discharge. C is the concentration of suspended sediment in mg L-1. The constant refers to the transformation factor of the units. The parameters were analyzed to identify trends within the analyzed historical series that may suggest hydrological trends that allow predicting phenomena. Some statistical patterns were used to analyze the chaotic disaggregation of the parameters, being mean, standard deviation and coefficient of variation (SIVAKUMAR, 2017).

Forecasts were made for the three parameters analyzed in the case of quotas and for the net discharge, the years 1995, 1996 and 1997 were used to forecast the data for the years 1998 and 1999. The years for analyzing the suspended sediment data were The years 1999, 2000 and 2001 were considered to forecast the data for 2002 and 2003. For this, the nearest neighbor method was used, according to Kember and Flower (1993), with a confidence interval of 95%. Predictions were compared with observed (actual) data to analyze the confidence level of the method. The historical analysis series is short, as non-linear forecasting methods for hydrological processes are discrepant in long-term analyzes (SIVAKUMAR, 2017).

5 RESULTS AND DISCUSSIONS

5.1 Flow Analysis and River Processes

Some concepts applied in Bénard's instability, which is a laboratory experiment to understand the dynamics, can be observed in nature far from the controlled environment that is the laboratory. The natural turbulence of rivers already presents chaotic movement, but the dynamics of helical flows is what comes closest to Bérnard's concepts (PRIGOGINE, 1993).

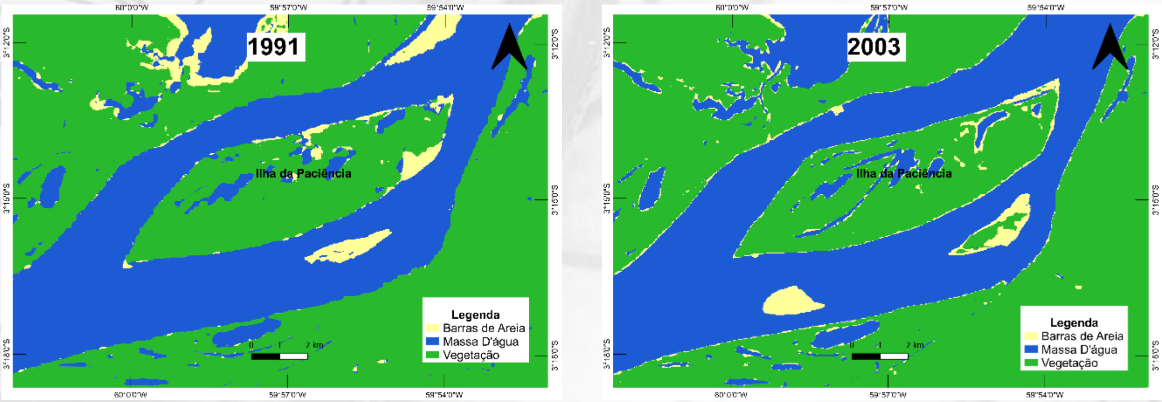
In the Solimões River, this flow occurs mainly in the confluence zone of the Solimões and Negro rivers, since according to Mosley (1975) and Best (1988), the confluence channels normally form a helical flow zone due to the presence of curvature in the flow line. Other areas may present a helical flow along the channel due to the roughness of the bed bottom, but in the zones of confluence channels this type of flow is more constant, making it difficult to predict the resulting hydrodynamic processes in the area and downstream.

In the area of Ilha da Paciência (Figures 03 a, b, c, d) it is possible to observe a silting up of Paraná on the right bank, the multitemporal analysis between 1991 and 2020 indicates that between 2003 and 2009 there was an accelerated process of deposition, resulting in significant changes in the fluvial processes of the lower Solimões area, while between 2009 and 2020 there was a stabilization of the vegetation, which characterizes the formation of new islands or the increase in the area of the island of Paciencia. Alves (2019) and Queiroz and Alves (2021) state, analyzing the deposition rates, that the tendency is for this margin to be completely silted up. The effects of this dynamic can already be observed on the left bank with an increase in erosion on the island of Xiborena, which is convex, i.e., conducive to erosion.

Queiroz et al. (2018) and Queiroz and Tomaz Neto (2019) state that in the region of the island of Xiborena the effects of bank erosion are felt with intensity compared to the areas upstream and the thalweg of the channel is migrating towards the left bank (FRANZINELLI, 2011; ALVES, 2019; QUEIROZ; ALVES, 2021), increasing hydraulic pressure, which is one of the main conditions for erosion in large rivers.

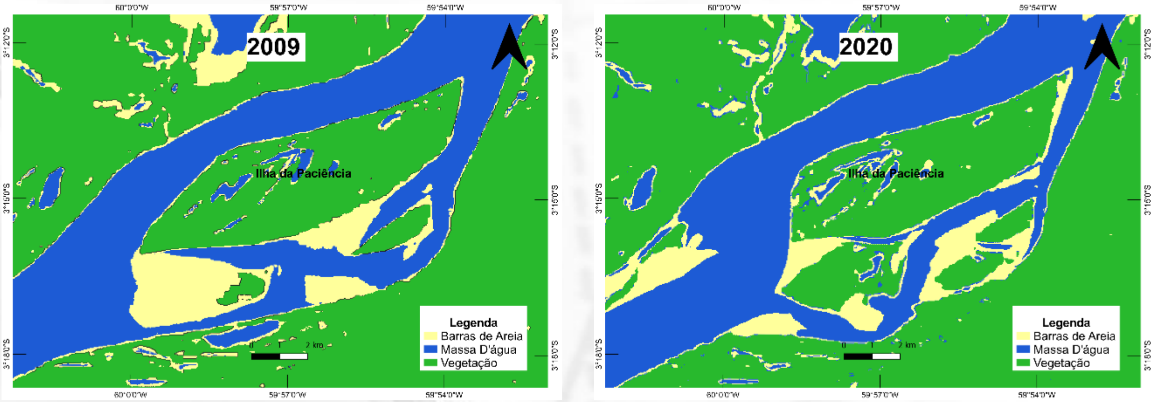
Figure 03 – Area of the lower course of the Solimões River, close to the confluence with the Negro River between the years 1991 and 2020 (A, B, C, D)

A) **B)**



Keep going…

C) **D)**



Source: Organization of the authors (2021).

It is observed that the silting up of the Paraná channel on the right bank of the island of Paciência triggered several factors that work separately, but integrated, in a way that directly influence the hydrogeomorphological dynamics of the lower course of the Solimões river and in the areas downstream, forming a dynamic not linear.

This denotes that initial conditions of the system will not necessarily indicate the final conditions. The resulting fluvial forms can bifurcate to different possibilities depending on the evolution of the local and regional hydrological dynamics. Therefore, it is possible to predict the conditions of siltation and increased erosion on the island of Xiborena in the short term, but the conditions in the medium and long term may change again, altering the fluvial dynamics and the resulting processes.

5.2 Analysis of Quota Data, Liquid Discharge and Suspended Sediments

The complex, irregular and apparently random nature of hydrological historical series and the lack of development of specific exact governing equations required in deterministic hydrological models motivated the improvement and applications of probabilistic and statistical methods for hydrological data analysis (SIVAKUMAR, 2017). Chart 02 presents important statistical patterns for the analysis of liquid discharge data, suspended sediments and fluviometric levels.

Chart 02 - Statistics of liquid discharge data, suspended sediments and levels for the lower course of the Solimões River (Manacapuru station).

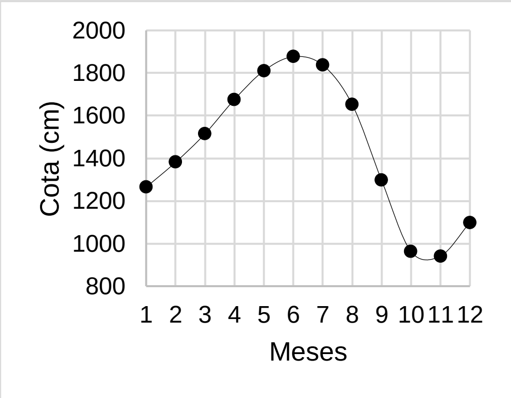
Statistics	**Liquid Discharge**	**Sediments in Suspension**	Quotas
Average	103.855 m³ s^{-1}	855.310 ton day^{-1}	1442,75 cm
Median	105.444,25 m³ s^{-1}	600.929 ton day^{-1}	1472 cm
Standard Deviation	27346,19	429180,8	335,847
Coefficient of Variation (%)	26,331	50,178	23,278
Maximum Value	140.616 m³ s^{-1}	1.499.732 ton day^{-1}	1876,75 cm
Minimum Value	63.344 m³ s^{-1}	340.493 ton day^{-1}	941,33 cm

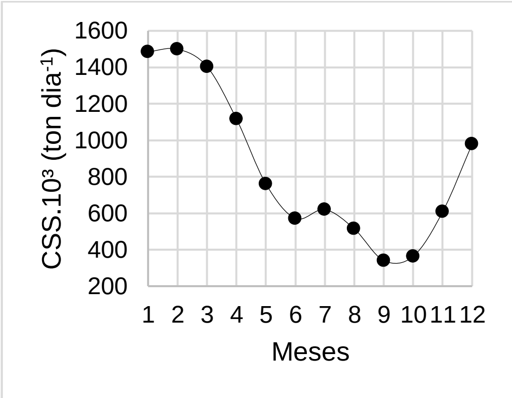
Source: Organization of the authors (2021).

The average is an important factor for the annual and monthly analysis of hydrological data, as well as the minimum and maximum value, as these factors can indicate trends in the time series. However, despite covering a certain amount of information, it is not a statistic that completely characterizes a time series. With the average values of a time series, it is possible to obtain the seasonality of the parameters and to predict in the long term the months with the highest and lowest values (Figures 04 a, b, c). However, the non-linear distribution of the data prevents a reliable forecast, since the data vary randomly over the analyzed series.

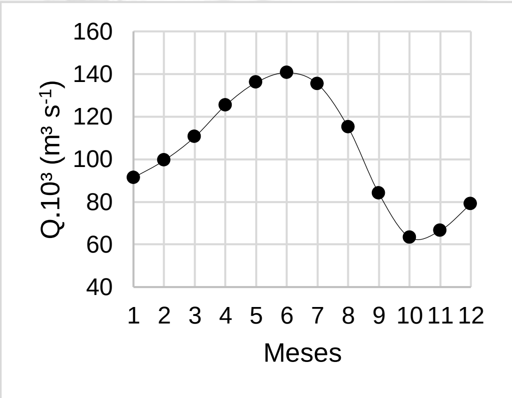
The median, like the average, is an interesting parameter for statistical data analysis, however it is observed that the non-linear trend of the data makes an in-depth analysis of annual and monthly data impossible. Standard deviation analysis is relevant to determine how uniform the data set is. The closer to zero, the more homogeneous the data. Among the analyzed data, the one with the greatest homogeneity is the quota and the most heterogeneous data are the suspended sediment data. The coefficient of variation is used to analyze the dispersion in terms relative to its average value, the elevation and liquid discharge data present a medium dispersion, the sediment data a high dispersion.

Figure 04 – Monthly averages of data on liquid discharge, suspended sediments and elevations for the lower course of the Solimões River (Manacapuru station, A, B, C).





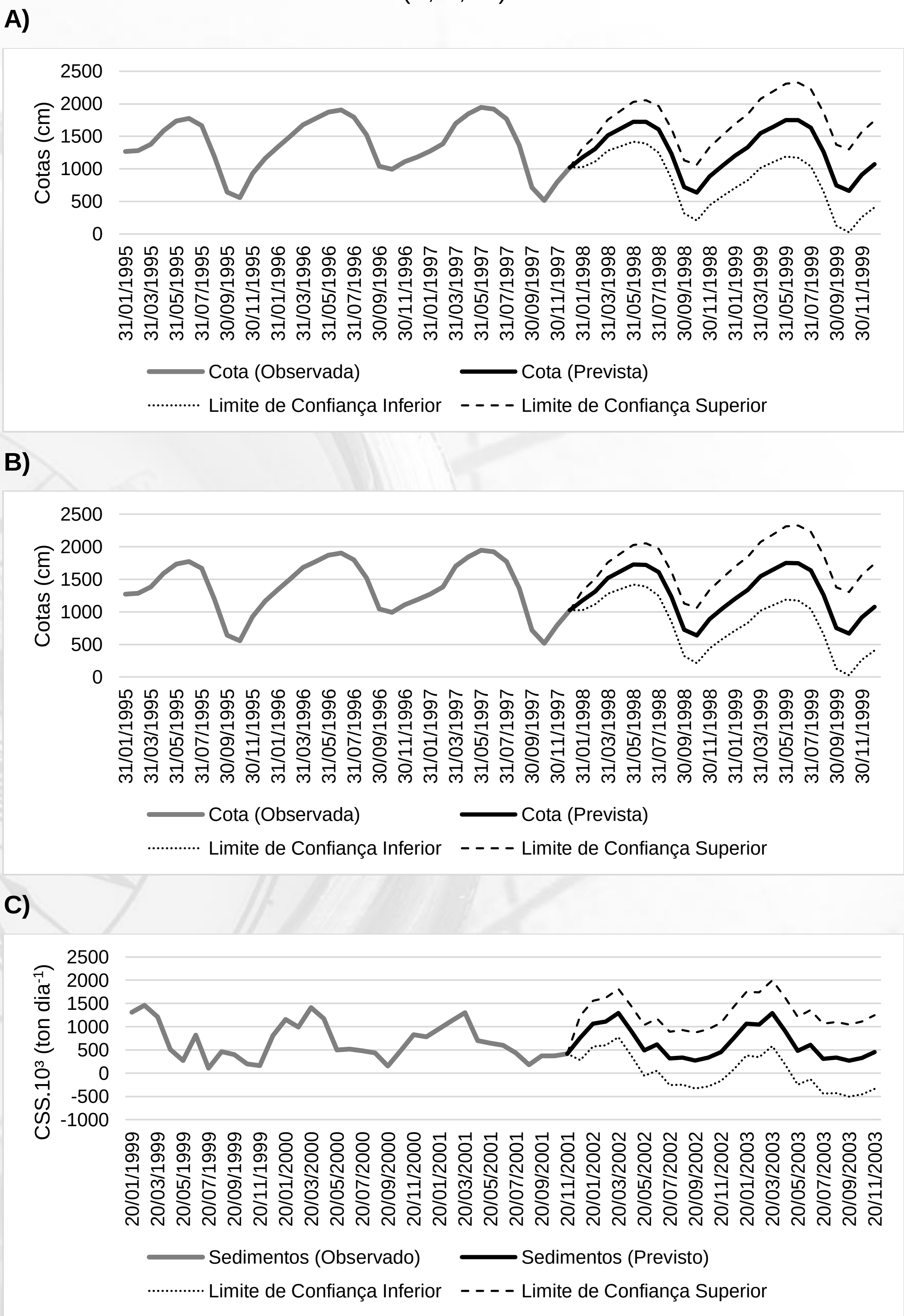
C)



Source: Organization of the authors (2021).
Note: A – Data from fluviometric measurements. B – Suspended sediment data. C – Liquid discharge data.

The idea of short-term forecasting of levels, discharges and sediments was also analyzed (Figures 05 a, b, c). It is observed that the data patterns are seasonal. Levels and discharge data have better data uniformity, therefore the margin of error for predictions is smaller, while sediment data are more random, it is noted that the confidence limit, in this parameter, has a greater amplitude and the lower limit presents negative values, which is not consistent with the reality in nature. This indicates the difficulty in predicting sedimentological data due to the apparent randomness of the data and its complex non-linear dynamics.

Figure 05 - Forecast of elevation data, liquid discharge and suspended sediments. (A, B, C.)

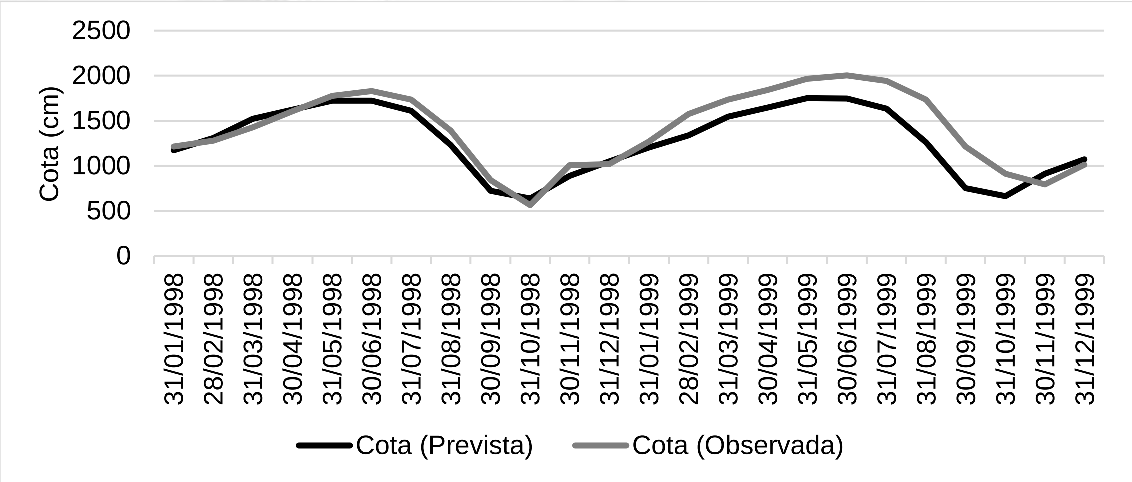


Source: Organization of the authors (2021).
Note: A – prediction of quota data. B – prediction of net discharge data. C – prediction of suspended sediment data.

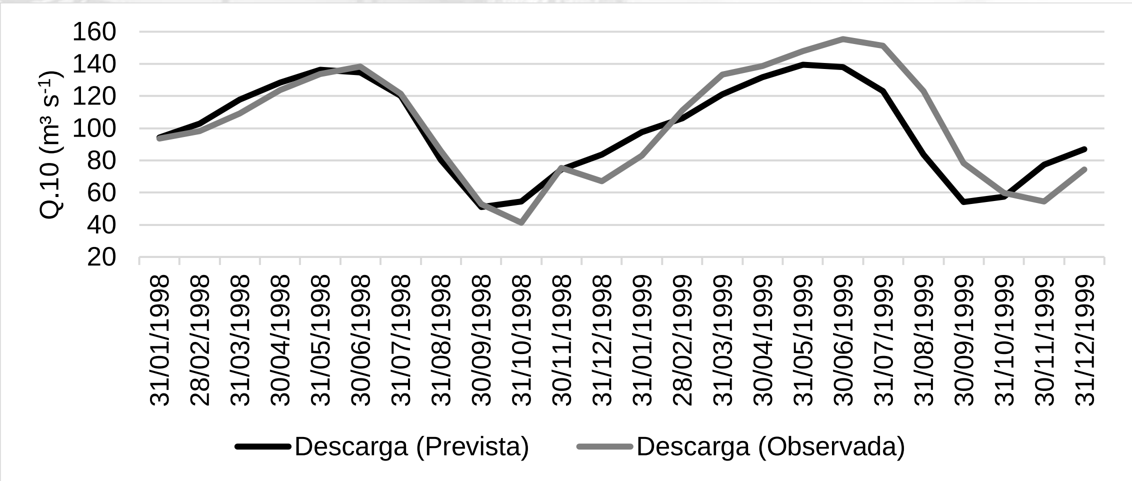
Comparing the predicted data with the observed ones (Figures 06 a, b) it is noticed that in the year 1998 for the data of quotas and discharges, the forecasts and the real data are similar. In 1999, it is observed that the data begin to diverge, but they are still within the stipulated margin of error (lower and upper confidence limits).

Figure 06 - Comparison of predicted and observed quota and net discharge data.

A)



B)

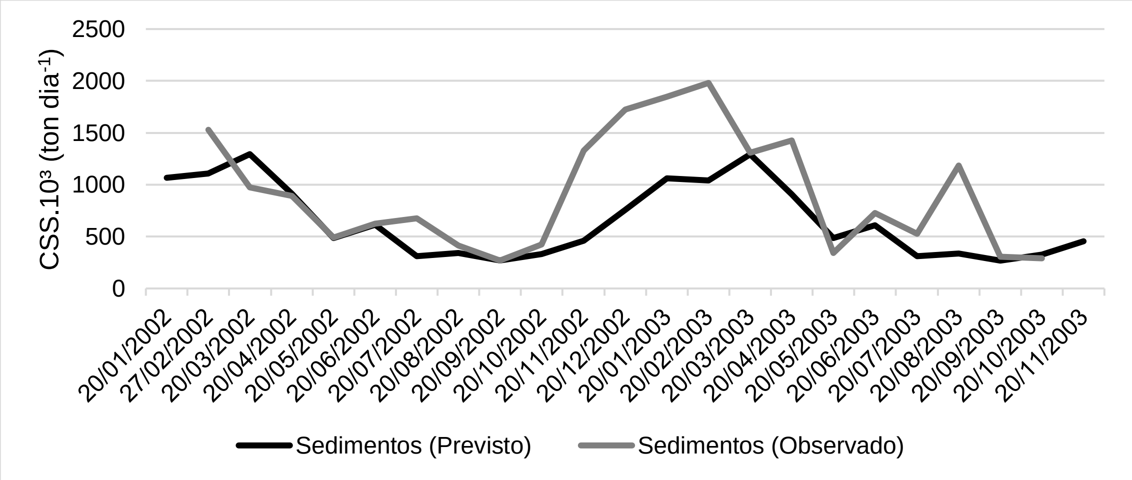


Source: Organization of the authors (2021).

Note: A – Comparison of predicted and observed quota data. B – Comparison of predicted and observed net discharge data.

Sediment data (Figure 07) are apparently more random, but follow the same dynamics, forecasts are closer to the real in 2002 and begin to diverge in 2003, but still within the confidence limit. The data prove that the predicted time series needs to be short, because, due to the non-linear characteristics of the data, the longer the predicted series, the greater the chance of inconsistencies between the observed and predicted data. The values of the standard deviation and coefficient of variation of the sediment data already indicate the non-linearity and apparent randomness of the sedimentological regime of the lower Solimões River.

Figure 07 – Comparison of predicted and observed sediment data in suspension.



Source: Organization of the authors (2021).

6 FINAL CONSIDERATIONS

Chaos Theory proved to be conducive to the analysis of river processes and flows. The analysis of turbulent flows and, in particular, helical flows, is interesting from the perspective of Chaos. It was observed that it is possible to predict the dynamics of these chaotic flows in a short time scale, but for medium and long term analyzes it is impossible to make predictions with a high degree of reliability about the local and regional hydrodynamic evolution.

The analysis of erosion processes and sediment deposition follow the same dynamics, it was observed that linear events (such as the linear deposition of sandy sediments that will result in silting up of the channel) can trigger unpredictable elements, making fluvial metamorphosis complex and non-linear.

When considering data on a smaller time scale, the predicted results for the years 1998 (quota and discharge) and 2002 (sediments) present a low margin of error, compared with the observed data, but the years 1999 (quota and discharge) and 2003 (sediments) begin to show greater data variability.

Therefore, it is necessary to forecast data for a short period of time, because the longer the forecast series, the greater the chances that the data will present inconsistencies. Forecasts of a short time scale can be important for predicting hydrological phenomena that cause structural, financial and human damage, facilitating the elaboration of public policies for disaster containment.

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