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Variability in the Negro River Water Level at Manaus, Brazil, Since 1902

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Abstract

Long-term observations of water level are scarce in Amazonia. The observations in the Negro River at the port of Manaus provide one of the few time series for more than 100 years in the Amazon Basin. We performed spectrum and trend analyses to understand long-term hydrological changes in the observed river levels at Manaus since September 1902. We obtained a significant long-term increasing linear trend of the order of 0.9 m in 122 years. The series of annual maxima and minima values, respectively, show stronger positive and negative trends. The annual minimum water level has lowered by 3.7 m, and the difference between the annual maximum and minimum levels has widened by 4.2 m since 1973. The spectra of the Fourier decomposition show the dominance of annual and semiannual cycles with amplitudes of the order of 4.1 m and 0.9 m, respectively. Other notable cycles present are the ENSO-related 3 - 6-year cycle, decadal cycle, and multi-decadal cycles of 40 to 60-year periodicity. The wavelet analysis also showed peaks of power at those periodicities. The Pettitt test obtained change points around the 1970s in the daily data series, as well as in the annual maxima series and annual minima series. Changes in the variability characteristics, both in the trends and the amplitudes of the cycles in the water-level series at the Manaus port, suggest changes in the climatic regime of the basin since the 1970s.

Keywords

Negro River Basin, Hydrological Extreme Events, Trend Analysis, Fourier Spectral Analysis, Wavelet Analysis

1. Introduction

The intensification of the hydrological cycle in the Central Amazon has led to record-breaking floods, as in 2021, and droughts, as in 2023 and 2024, in the region [1] [2]. In Manaus port, the reference level of 29 m indicates that many riverine communities are affected by inundations, and the city center of Manaus is flooded; such situations were observed six times in the last 20 years [1]. When the water level decreases to 15 m or lower, fluvial transport and other important economic activities are hampered, causing serious problems for the people of the region [3]. Such dry situations have been observed in the last quarter century, spanning seven years. The extreme situations also seriously affect the fish production in the floodplains of the Amazon basin [4].

Two distinctive characteristics of the Amazon climate are the monsoon regime with strong seasonality of rainfall, the root cause of river level variability, and a rapid transition from the basin's rainy season to dry season [5]. Besides that, there have been important trends, with decreasing rainfall over the southern basin and increasing rainfall over the north and west since 1980. [6]-[8] found that the main variability of rainfall in the basin is at decadal and inter-annual time scales.

Frequent adverse effects felt by the society of the region due to the variability of the water level call for efficient seasonal forecasts. [7] showed a 26% increase in maximum floodplain inundation in the Amazon since 1980, with an increasing trend in rainfall in the northern portion of the region. Understanding the observed variability of the Negro River level can help scientists and engineers to monitor and issue appropriate warnings and alerts to the people in the basin.

In spite of the studies mentioned and the knowledge gathered, some important questions remain to be answered. They are: What and when did significant changes in the variability of water level in the central Amazon Basin occur, and how great were these changes? Are there significant trends in the mean and in the annual extrema of water level at Manaus port? What are the important cycles present in the water level observations, and have they undergone changes? The present study attempts to answer the questions by investigating the long-term trends and oscillations in the river level at Manaus port.

Thus, the objectives are to find and describe: a) the trends, if any, in the long series of river level data from 1902 to 2024 at the port of Manaus; b) the trends in the subsets of the annual maximum level and minimum level and their difference (annual range) data; c) the amplitude spectra of cycles in the datasets.

2. Data and Analysis

There are daily measurements of the Negro River level at the Manaus port (3.12˚S; 59.95˚W) (**Figure 1**) since September 1902. The observations are made manually daily once at 12 UTC (08 LT) by trained personnel of the port with the help of the limnimetric ruler (water-level gauge) installed on the wall of the port in 1902. No changes were made in the position of the ruler. Presently, the data can be obtained from HidroWeb of the National Agency of Water and Basic Sanitation (acronym ANA) of Brazil (https://www.snirh.gov.br/hidroweb).

Negro River basin has an area of 716,000 km^2 and is an important tributary of the Amazon River, contributing 14% of the total drainage into the Atlantic Ocean. The basin is mostly forest-covered and flat except in the north along the Brazil-Venezuela border, where 1 km high mountains are situated. Manaus lies at the mouth of the river.

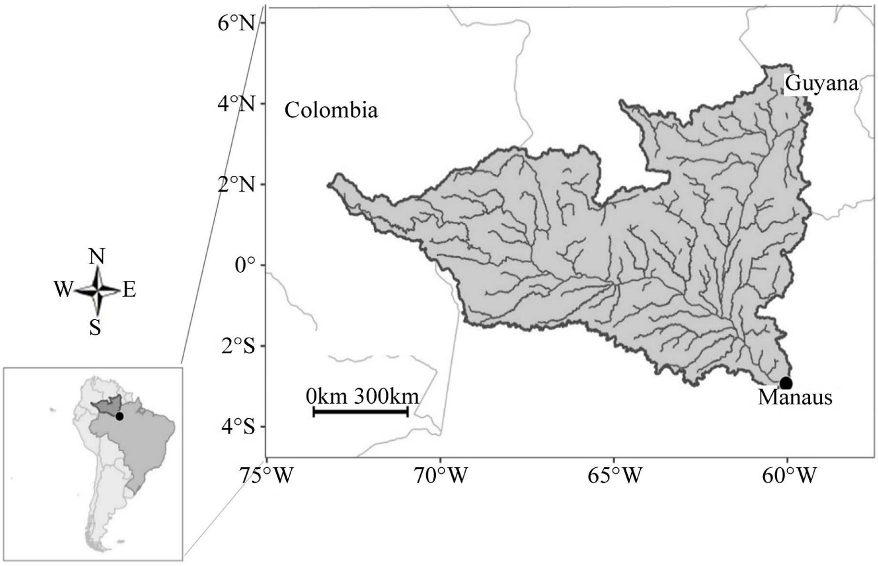

Figure 1. Location map of the Negro River basin and the Manaus port (3.12˚S; 59.95˚W).

Annual maxima series, and minima series of the river level and their differences (annual ranges) are extracted from the daily series. Initially, the plots of the series are examined visually to assess the gross qualitative characteristics of the variability of the river level. Then the series are subjected to mathematical analyses.

2.1. Trend Detection

Long-range linear trends in the series are detected by performing the Mann-Kendall (MK) test [2] [9].

Sen's slope, s, is calculated for quantifying the trend of the water-level series h_n, n = 1, 2, 3, ..., N, where N is the sample size. It is the median value of all slopes:

$$d_k = (h_j - h_i)/(j - i) \text{ for } (1 \le i \le j \le N) \quad (1)$$

That is, Sen's slope is the median of all the slopes obtained from pairs of data, restricted to the condition $j > i$. The linear trend equation is given by

$$h_n = s\,(n - 1)\,\Delta t + c \quad (2)$$

where c is the intercept and Δt is the data spacing.

The unit of time in the case of daily data is $\Delta t = 1$ day and for the annual maxima and minima data, it is 1 year. The units of s are (m day^{-1}) for the daily data and (m year^{-1}) for the yearly data.

2.2. Amplitude Spectra

Fourier decomposition (harmonic analysis) [10] is performed to find the cycles in a given time series. The amplitudes of the cycles are plotted against cycle periods (or frequencies), and the graph is designated an amplitude spectrum. The harmonic analysis of a regularly spaced dataset over an interval t = 0 to t = T assumes a cyclicity of T. The analyzed cycles have periodicities which are integral subdivisions of T, that is, T/m, m = 1, 2, 3, … M, where M = N/2 − 1 for N even, or M = (N − 1)/2 for N odd, in which N is the number of data points (sample size). The m^th^ harmonic is given by

$$H_m = A_m \cos(2\pi m t/T - \varepsilon_m) \tag{3}$$

where A_m and ε_m, respectively, are the amplitude and phase angle of H_m. Its periodicity is T/m.

The variance explained by the harmonic is given by

$$\mathrm{Var}(H_m) = A^2{}_m/2 \tag{4}$$

The sum of the variances of all the harmonics is equal to the total variance of the series, V. That is,

$$\sum_{m=1}^{M} A_m{}^2/2 = \mathrm{V} \tag{5}$$

Thus, the importance of the m^th^ harmonic is measured by the variance explained by its amplitude as a percentage of the total variance:

$$[\mathrm{Var}(H_m)/V] \times 100 \tag{6}$$

The cyclicity assumption of the series affects the first few harmonics. Also, this analysis has problems of aliasing near the Nyquist frequency, $f_N = 1/2\Delta t$, and near the Rayleigh frequency $f_R = 1/N\Delta t$ [11]. Away from f_N and f_R the results are interpretable, especially for large N. Due to the long-period trends in the dataset, the amplitudes near f_R show high values. In order to remove the possibility of misrepresenting the trends as cyclic behavior, the trends are subtracted from the original datasets, and the resulting series are subjected to harmonic analysis in this study. That is, the new series is subjected to the decomposition into cycles.

$$h_n' = h_n - [(n-1)s + c] \tag{7}$$

2.3. Wavelet Analysis

The cycles in the series and their power distribution during the period of the series can be obtained by applying wavelet analysis [11]. This analysis gives us, besides the general spectrum, the power of the cycles in periodicity versus time and space. The power of a particular cycle in which we are interested can be extracted. The power tells us the importance of the cycle.

2.4. Break Point or Change Point (CP) Analysis

Pettitt test [12] [13] is applied to obtain the break point (or the change point) and its significance. The analysis quantifies the change in the mean and median of the series before the change point and after the change point.

2.5. Software

The software R (https://www.r-project.org) is employed for these analyses. As there are indications of increasing annual range of the water level (see Section 3.1), especially in the last half century, Mann-Kendall trend analyses and harmonic analyses were performed for two separate periods of data: 1902-1978 and 1979-2024. The Negro River level variability is discussed in light of the results of these analyses.

3. Results

3.1. Visual Examination of Data

Figure 2 presents the plot of the whole 122-year dataset containing 44,682 observations. There are no gaps or missing data in the series. Visual examination of the plot reveals the following notable points. Except in 2021, the river level did not surpass 30 m. Only in 1912 and 1926 were the yearly maxima lower than 25 m. These two years can be considered exceptional. Peaks near or higher than 29 m occurred in 24 years out of 122, that is, about one in five. In the last 15 years, from 2010 to 2024, there were 6 such peaks. In May 2021, the water level reached 30.02 m, the record high so far.

The annual minima remained higher than 22 m in just four years and went below 14 m on just four occasions out of 122. If the series remains stable, one can say that the annual minimum river level remains between the limits of 14 - 22 m and the annual maximum remains between the limits of 25 - 30 m. Any event beyond these limits can be considered exceptional.

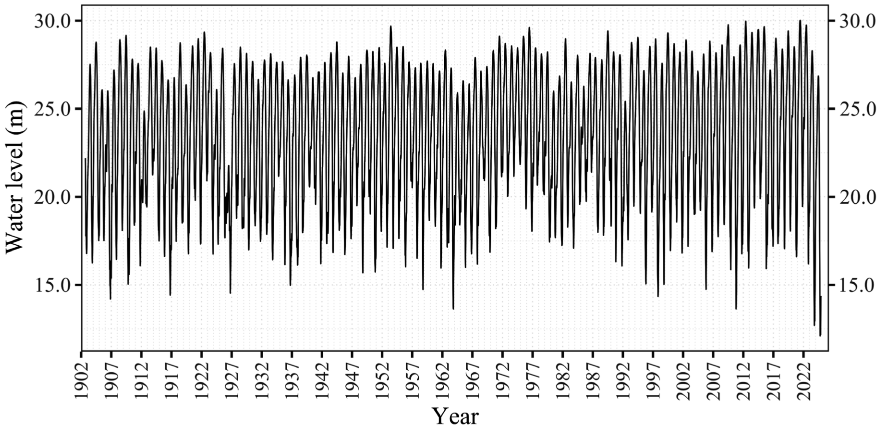

Figure 2. Negro River level (m) at Manaus Port, Brazil—historical daily data from September 1902 through November 2024.

Figure 3 presents a zoom of the series in the 5-year period January 2020-November 2024. First, we observe that the variability of the river level is smooth. The annual maxima of the river level occur around June, and the annual minima around

December. The rise of the level takes longer, around seven months, and the fall of the water level is faster, around five months. Thus, the water level series has a negative skewness (*i.e.*, rising limb slower than the receding one), which has been attributed to floodplain storage effects upstream along the Amazon River [7]. There are indications that in the middle of the rising season, the rise either slows or even the water level dips a little, as can be seen in the year 2022.

Inspection of **Figure 2** indicates that the annual range of water level has had a widening tendency since the mid-1970s. In the past half a century, the annual maxima frequently rose close to or higher than 29 m, and the minima lowered below 15 m. The increase in the frequencies of intense extrema events (h ≥ 29 m, h ≤ 14 m) after the mid-1970s is noteworthy. Such changes are noted by [7] and [8], who have attributed the intensification of rainfall to the intensification of the Walker circulation driven by the temperature difference between the tropical Atlantic and the tropical Pacific. [14] have analyzed the atmospheric circulation and identified the inter-ocean temperature contrast and the changes in the Walker circulation.

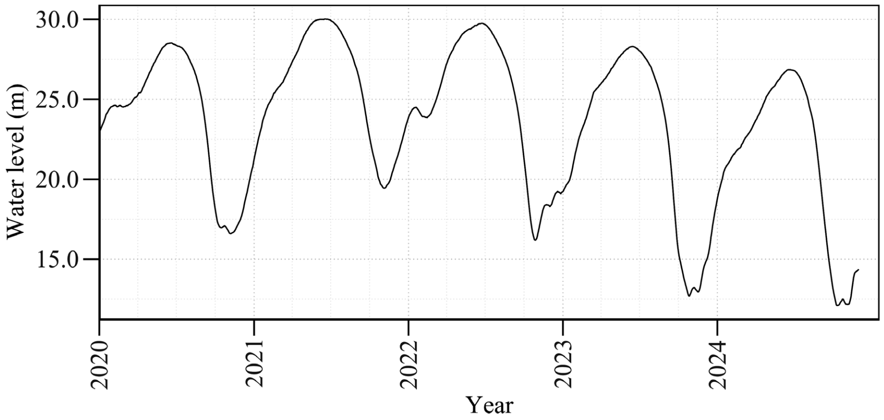

Figure 3. Zoom of the Negro River level series for the period 2020-2024.

3.2. Trend Analysis Results

The daily water-level data, the yearly maximum level data, the annual minimum level data, and the annual range (annual maximum minus minimum) datasets are subjected to the MK test. First, the series analyzed are tested for autocorrelation (AC), and we found that AC decreased with lag in daily and annual series of data up to lag 4, as it should be in the presence of trends [15]. The MK test and Sen´s slope results are given in **Table 1**.

The whole series and the two parts of the series of daily observations of the water level at Manaus port show significant positive trends. The annual maxima for the whole period showed a small positive trend, but the minima and the range do not present a significant trend.

However, minima showed a strong negative (decreasing) trend for the period 1973-2024, while the maxima showed a positive trend. These opposite trends in the annual maxima and minima amount to a strong positive trend in the annual range. The trends up to 1972 and after 1972 are different, indicating changes in the series at around the mid-1970s, agreeing with earlier findings of [8].

Table 1. MK trend analysis and trend equations of the series of water level observations at Manaus port. Period: Data length in years. S: MK statistic (nondimensional). t is time and its coefficient s is Sen's slope. The constant is the intercept, the value at t = 0 according to the trend line. (D) and (Y) indicate, respectively, daily and yearly data.

	Period	MK statistic	p-value	Trend	Equation h = s t + c
1	**1902-2024 (D)**	20.469	2.22×10^{-16}	Positive	h = 0.00002 t + 22.88
2	**1902-1978 (D)**	14.699	2.22×10^{-16}	Positive	h = 0.00004 t + 22.67
3	**1979-2024 (D)**	9.588	2.22×10^{-16}	Positive	h = 0.00003 t + 22.63
4	**Maxima (Y) (1903-2024)**	3.831	0.00013	Positive	h = 0.011 t + 27.23
5	**Minima (Y) (1903-2024)**	0.215	0.83003	No trend	h = −0.001 t + 17.52
6	**Range (Y) (1903-2024)**	1.921	0.05475	No trend	h = 0.0125 t + 9.71
7	**Maxima (Y) (1973-2024)**	2.044	0.04095	Positive	h = 0.012 t + 27.83
8	**Minima (Y) (1973-2024)**	−3.685	0.00023	Negative	h = −0.070 t + 19.47
9	**Range (Y) (1973-2024)**	4.435	9.21×10^{-6}	Positive	h = 0.089 t + 08.37

The trend equation for the whole series of 44,682 daily observations shows that the intercept is 22.8 m. This is the value at t = 0 according to the linear trend line. The slope of the linear trend is approximately 0.9 m rise in 122 years. The period 1902-1978 showed a larger positive trend. More significant and interesting results are obtained for the annual maxima (floods) and minima (droughts) for the period 1973-2024. The annual maxima have increased at the rate of 1.2 cm year^{-1}, equivalent to an increase of 0.612 m in the 51-year period. The annual minima have decreased at a faster rate: 3.57 m in 51 years. As a result, the yearly range of water levels at Manaus port has widened by 4.18 m over the recent half-century.

The annual maximum and minimum values and their difference (annual range) are plotted in **Figure 4** along with the trend lines for the period 1973-2024. The annual maximum lowered below 25 m only in two years, 1912 and 1925. The extreme case of a very low annual maximum of around 21.5 m happened in 1925. The annual maximum values reached or surpassed 29 m five times till 1979, and from 1980 to 2024, the water level rose above 29 m 11 times, indicating an increase in the severity and frequency of flood events as was noted by [7].

The annual minimum was above the line of 20 m on 7 occasions in 122 years. The minimum dropped below 14 m only in four years: 1964, 2010, 2023, and 2024. Except for the event in 1964, the other three are recent events that happened after 2009. The decreasing trend of the annual minimum since the mid-1970s is evident. The mean annual range of water level for the whole period is 10.48 m with a standard deviation of 1.92 m. However, it oscillated around 9.7 m until 1975 and increased rapidly in the last half a century, as is shown in black (**Figure 4**), from 8.4 m in 1972 to nearly 13.0 m in 2024. It is also seen that the fall of the annual minimum was faster than the rise of the annual maximum.

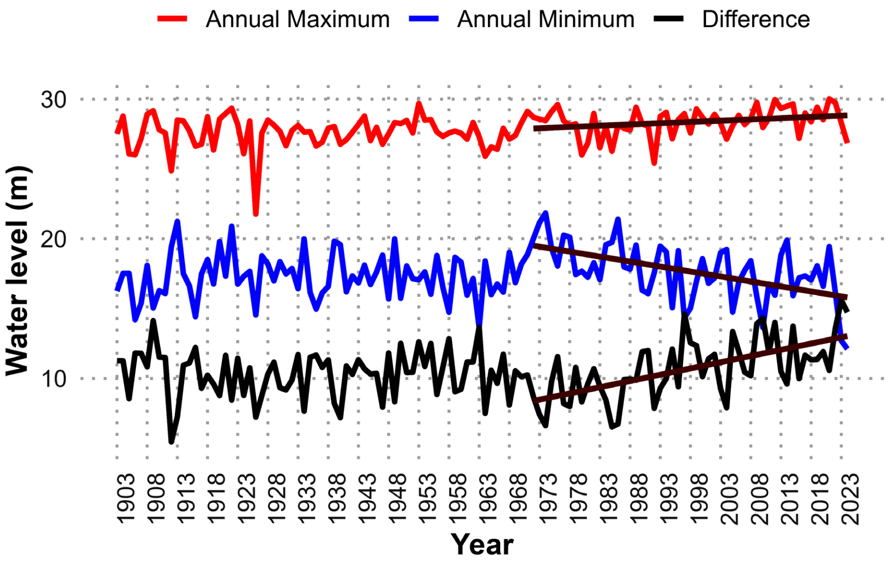

Figure 4. Annual maxima (red), minima (blue), and the range (black) values for the 122-year Negro River level series for 1903-2024. The straight line segments are linear trend lines for the period 1973-2024.

[14] presented a plot of Manaus port data up to the year 2015. Their analysis showed that the variability of the Amazon hydrologic cycle intensified from the late 1990s to 2015 with a marked increase in severe floods. We see from **Figure 2** and **Figure 4** that these changes started in the mid-1970s and continued after 2015. Furthermore, we found that the increase in severe droughts is more marked.

3.3. Cycles in Water Level at Manaus Port

Figure 5 shows the amplitude spectra of the series of the Negro River water level at Manaus port for the whole period after removing the linear trends (Equation (7)). We should mention that large amplitudes were obtained for the cycles near the Rayleigh frequency, $f_{R.}$ (122-year, 61-year, and 40-year cycles) before trend subtraction (not shown). They are not seen in **Figure 5**.

The spectrum for the whole period with daily observations (**Figure 5(a)**) indicates that there are no appreciable amplitudes for high-frequency cycles (periodicity ≤ a few months). That is, the mid-latitude synoptic-scale effects are not significant in the Negro River basin. We note that the annual (seasonal) cycle is dominant with an amplitude of 4.1 m (the tallest line). This is equivalent to the annual range of 8.2 m. The semiannual cycle also shows a significant amplitude of nearly 0.9 m. The dips observed in the middle of the rising limbs of the annual variation of water level seen in **Figure 3** are manifestations of the semiannual cycle. A 16-

year cycle is also present with smaller amplitude in the spectrum.

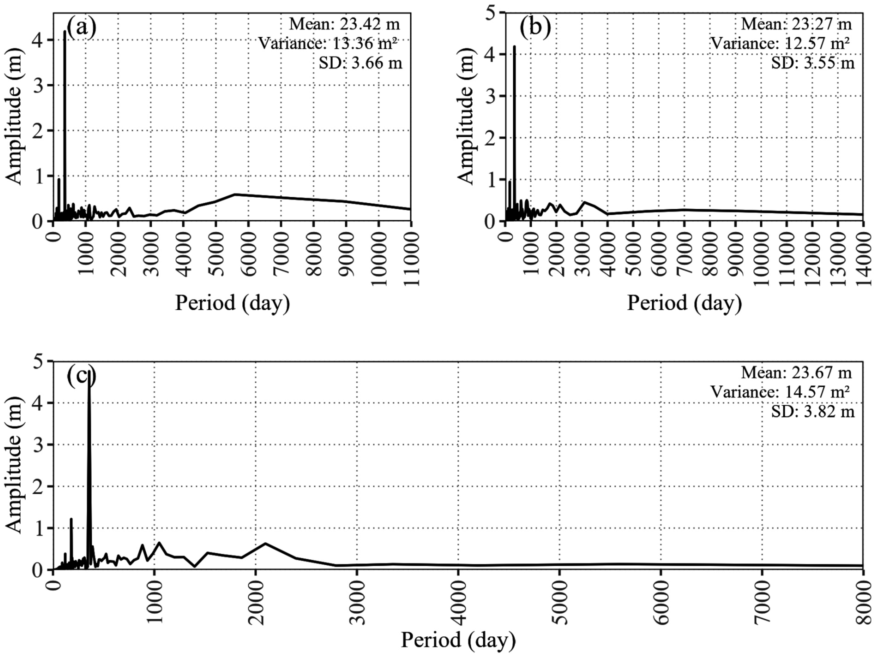

Figure 5. Amplitude spectra of the Negro River level at Manaus. (a) for the whole period Sep 1903-Nov 2024 with daily observations; (b) for the period September 1902-December 1978, daily observation; (c) for the period January 1979-December 2024, daily observations.

Suspecting a regime change around 1980, the series is divided into two parts, 1902-1978 and 1979-2024, and the harmonic analyses were performed separately for the two parts. The spectra are shown in Figure 5(b) and Figure 5(c). We find notable differences in the spectra of the two periods of data. In the first period (Figure 5(b)), the amplitude of the annual cycle is 4.1 m as against 5.0 m in the later period (Figure 5(c)). The semiannual oscillation also shows a small increase in its amplitude from the early period to the later period. The ENSO-related 3 - 6 year periodicities and their amplitudes also have changed somewhat. The peak at a 5-year period became higher with nearly 0.5 m and well defined in the later period. The 16-year cycle also became stronger. These changes in the cycles and the changes in the trends (compare Sen's slopes in Table 1) indicate that the climate regime changed around the early 1980s, also reported by [8], and are considered worth noting.

Figure 6 shows the amplitude spectra for the yearly values of maxima, minima, and their differences for the whole period. The amplitudes in all time scales are higher in the minima series than in the maxima series. For example, the 16-year oscillation in the maxima has an amplitude of 0.36 m, whereas the minima show an amplitude of 0.56 m. The oscillations related to ENSO (3 to 6-year period) show amplitudes of 3.3 m in the maxima and 6.5 m in the minima, indicating that ENSO affects the intensity of droughts more than the intensity of floods. If El Niño happens to affect the rainfall in the Negro basin during the drought season, the deficiency or lack of rainfall reduces the water level, which is already low due to the seasonal effect, further exacerbating the issue. The inundated area in the drought period is small. Any reduction in rainfall due to the ENSO effect can cause the riverbed to dry out or drastically lower the water level in it. The forecasters are advised to pay more attention when the El Niño becomes active during the dry season in the basin.

The 40-year and 60-year cycles have amplitudes of the order 0.2 m for the annual maxima, 0.6 m for the annual minima, and 0.8 m for the range.

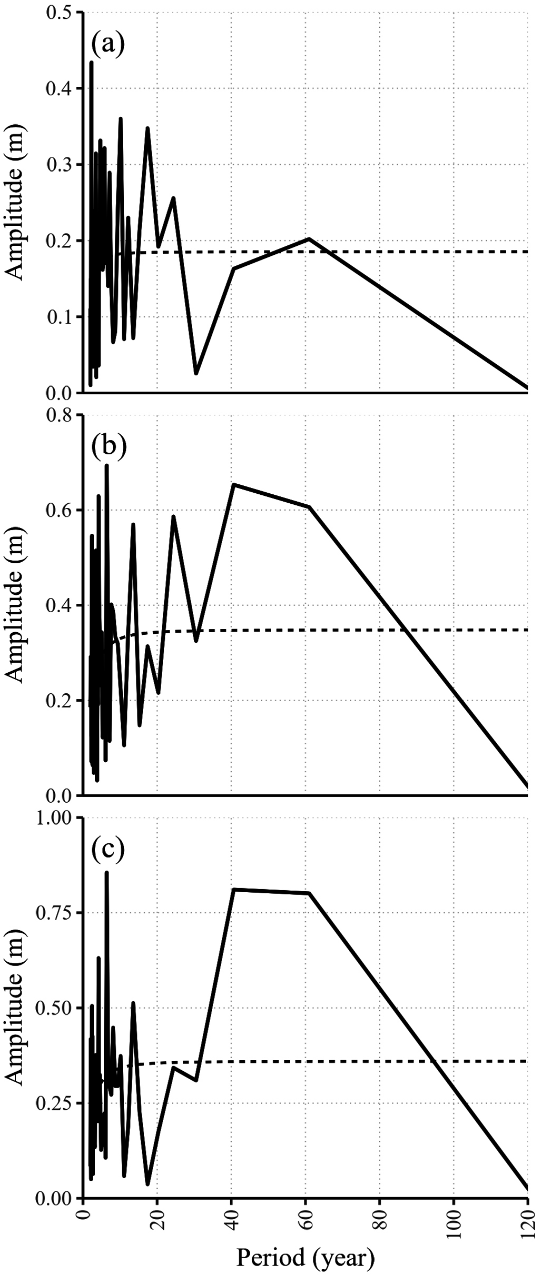

Figure 6. Amplitude spectra of the Negro River level annual: (a) maxima, (b) minima, and (c) their differences (annual range). Dashed line (red noise).

The multi-decadal cycles (40- and 60-year) present the same order of magnitude for their amplitudes as the 3 to 6-year cycles for the annual minima and for the range. In the annual minimum and the annual range datasets, the amplitudes are greater than those of the red noise spectrum. The reasons for the multi-decadal cycles are not known. In fact, to ascertain the presence of significant multi-decadal cycles, data for over two centuries are required.

3.3.1. Phase Spectrum

Figure 7 presents the phase angles (ε_m) of the cycles in the series of annual minima for the whole period corresponding to **Figure 6(b)**. For the sake of interpretation of the figure, we take the example of the (multi-decadal) 40-year cycle. It has an amplitude of 0.65 m (**Figure 6(b)**). For this cycle, 2π radians correspond to 40 years. The starting point of the series is 1903, and if the phase angle were zero, the maximum of this cycle occurs in 1903, and subsequent maxima of this cycle occur at intervals of 40 years. If the phase angle is $-\pi$ (or $+\pi$), the first maximum occurs 20 years later or before 1903, and the minimum occurs in the year 1903, and the subsequent minima are repeated every 40 years. In **Figure 7**, the phase angle of the 40-year cycle is nearly $\pi/3$ radians, corresponding to approximately 13 years. That is, the peak of the annual minimum level in the 40-year cycle should occur in 1916, repeating every 40 years thereafter. However, in reality, the multi-decadal cycle may not present a definite periodicity. These low-frequency cycles and the SOI-related cycles are not stationary. The cycle periods can vary from time to time, unlike the annual and semiannual cycles that follow regular solar radiation forcing. Attempts to forecast the occurrence of floods and droughts with long lead times using the multi-decadal cycles are more likely to fail. The amplitudes and phases of annual and semiannual cycles are determined accurately. Such information is helpful to forecasters.

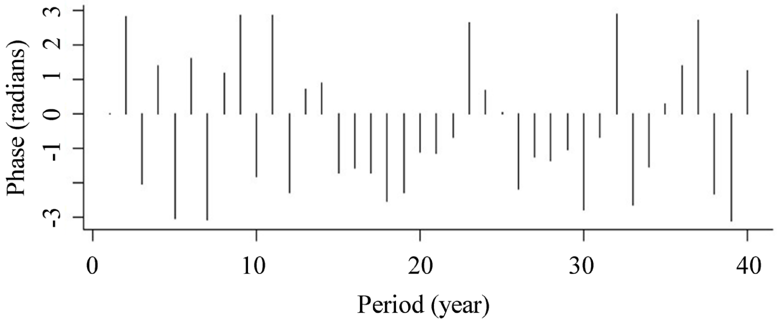

Figure 7. Phase angles of the cycles in the series of Negro River level annual minima in the period 1903 to 2024, corresponding to **Figure 6(b)**.

3.3.2. Variance Explained by Cycles

To appreciate the relative importance of the cycles, the variances of the series explained by each cycle in the spectrum shown in **Figure 5(b)** are plotted in **Figure 8(a)**. The semiannual and annual cycles are responsible for 3% and 64% of the variance of the series, respectively. The other cycles individually explain very little variance. Figure 8(b) presents the same graph after suppressing the annual and semiannual cycle contributions. The 16-year cycle, the third prominent cycle, explains about 0.5% variance only. The ENSO-related cycles (3 to 6-year cycles) explain even less.

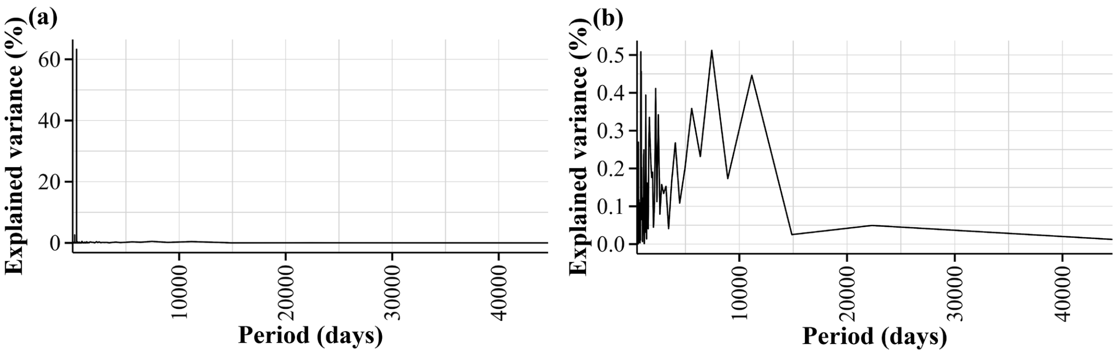

Figure 8. % variance explained by the cycles in the water level data at Manaus port for the period 1903-2024: (a) all cycles; (b) cycles beyond the 2-year periodicity.

3.4. Wavelet Analysis

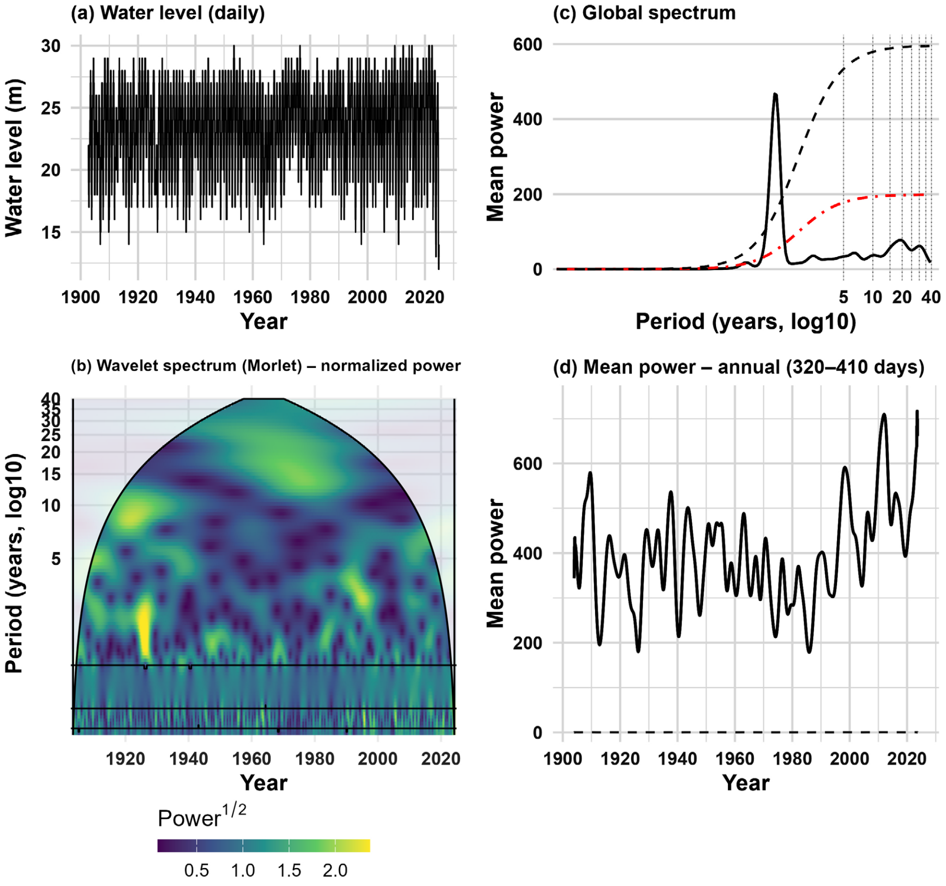

Figure 9. Wavelet analysis of Manaus water level: (a) series; (b) Morlet spectrum (normalized); (c) global spectrum: solid = mean; upper dashed line = 95% confidence interval; red dot-dash = red noise; (d) annual-cycle power variation.

The wavelet spectrum analysis of the water level data for 122 years is shown in **Figure 9**. **Figure 9(a)** shows the series. **Figure 9(b)** shows that the variability of the power of the cycles with periodicities of 1 - 12 years during the period of 122 years is high. **Figure 9(c)** shows the dominance of the annual cycle. All the peaks other than the annual and semiannual cycles are below the red noise. However, there are peaks in power for the decadal and inter-decadal cycles. The spectrum shows that the high-frequency variability (periodicity < a few months) is negligible. **Figure 9(d)** shows that the power of the annual cycle has grown since the 1980s. This is related to the positive trend in (or the widening of) the annual range of the water level.

3.5. Pettitt Change Point Analysis

The change points in the series and the changes in the median values before and after the change points are given in **Table 2**. The three series shown in the table point to changes around the end of the 1960s, and according to the p-values, the changes are significant (< 0.05). The changes in the median value from before and after the change point were of the order 0.6 m in the annual extrema and 1.0 m in the daily values. These results corroborate the changes found in the trend and spectrum analyses for the early period and later.

Table 2. Pettitt break point test results. n is the size of the dataset, Δ Median is the change in median values from before to after the change point.

Dataset	Data Period	Change Point	p-value	Median Before	Median After	Δ Median
Daily (n = 44,638)	1902-2024	1970	2.85×10^{-22}	23.0 m	24.0 m	1.0 m
Annual minimum (n = 122)	1903-2024	1967	0.04	17.15 m	17.74 m	0.59 m
Annual maximum (n = 122)	1903-2024	1969	0.0002	27.65 m	28.46 m	0.61 m

4. Discussion

[8] mentioned that the main variability of the precipitation in the Amazon basin is in decadal and interannual time scales. In our study, we found the variability is in seasonal, semiannual, decadal, and multi-decadal time scales. The present study is based on a longer series than those used in the studies of [8] and [14]. For the first time, we made calculations of trends and cycles in the series of annual maxima and minima separately and explicitly. The annual maxima and minima sets show opposite trends, causing the annual range of water level to widen since 1973. This result is different from [14], who stated that the intensification of the Amazon hydrological cycle started in the late 1990s.

Water level variations in large low-lying and free-flowing river systems in the Amazon basin, such as the Negro basin, follow large-scale precipitation anomalies [16]. The river level variation is an integrated effect of the rainfall over the whole basin upstream of the gauging station, and also responds to hydrodynamic processes such as backwater effects, especially over lowland rivers [17]. The Negro River water level variability near the confluence with the Amazon River is related to the rainfall variability in the Negro basin (**Figure 1**) and the backwater effect of the Amazon (Solimões) River. When the water level in the main branch of the Amazon River rises due to intense rainfall in the western Amazonia, it reduces or blocks the flow of the Negro River. This reduction in drainage accumulates water upstream of Manaus, and as a result, the water level of the Negro River rises even if there is no increase in the rainfall in the Negro basin. The water level variation in the Negro River at Manaus actually reflects the complex interaction between upstream hydrology in the Negro River basin and the hydrological processes in the Solimões River Basin. The Solimões-Amazon backwater influence along the Lower Negro River has been described by [17], and its influence goes as far as 400 km upstream along the Negro. Thus, to understand the variability of the Manaus water level, it is necessary to understand the hydrology of the whole Amazon basin upstream from the Negro-Solimões confluence. Due to multiple effects acting on the water level at Manaus port, the variability becomes complex. Spectral analysis can find the dominant cycles. This knowledge is valuable for the hydrologists and meteorologists of the region.

The Pettitt change-point analysis is appropriate to find the changes in the means and medians of the series before and after the change point. In the annual extrema series of the water level at Manaus, significant changes occurred in the trends during the 1970s, as shown in **Figure 4**. The maxima show an increasing trend and the minima a strong decreasing trend that may be alarming for the hydrologists, meteorologists, and the riverine communities in the region. The analysis detected a change point and the changes in the mean and median water level from before to after the change point. However, the changes from before the 1970s and later are in the trends of the series, as can be seen in **Table 1** and in **Figure 4**. Therefore, the visual inspection of the series and separate trend analyses for the two periods (up to 1973 and later) gave us additional information.

The river level data at the Manaus port is a long and robust series of hydrological information. This historical uninterrupted series of 122 years can reveal many characteristics of the variability of the water level in the past and, consequently, the climatic variability and change in the basin, if any.

The variability of the river level is composed of long-term trends, considered changes in the hydro-climatic regime, and oscillatory behavior. The trends and changes are basically due to global warming and regional land surface changes, mostly related to anthropogenic practices, as seen in the study of [18], who found that the storm runoff extremes are projected to become more frequent and damaging due to a warming climate and anthropogenic changes. [19] have stated that extreme precipitation events will become more common in an anthropogenically warmed climate. [20] analyzed the projections of the global hydrological models with 21 scenarios of global changes and found that the models project a decrease in runoff in Brazil. These studies indicate that changes in streamflow are expected in a globally warming climate due to anthropic activity. Although the present study shows that the annual cycle is becoming more intense, the drought period runoff (taking water level as a proxy) is decreasing faster than the flood period runoff. On the annual average, the runoff may decrease as is projected by [20] for Brazil. The Amazon basin is a complex system, with contrasting trends across it. Recent studies have pointed to an intensification of the hydrological cycle in the south of the basin (*i.e.*, more extreme floods and droughts), with a wetting cycle in the north (*i.e.*, more extreme floods) [21]. In Manaus, there has been an increase in the overall annual amplitude of the water levels.

Ocean-land-atmospheric systems may have some natural oscillations, such as the Madden-Julian Oscillation, annual and semiannual cycles, and the ENSO. In reality, the oscillations do not have a definite periodicity. For example, the periodicity of the Madden-Julian Oscillation is anywhere between 30 and 60 days [22]. The periodicity of El Niño is observed to be anywhere between three and six years [23]. Similarly, the periodicities of decadal and multi-decadal oscillations are also not definite. Therefore, any attempt to extrapolate climate or to forecast the extreme events by using the cycles observed in a historic time series does not work. However, annual and semiannual cycles are very regular, and the gross features of the seasonal variability are possible to estimate and forecast.

Due to their adverse effects, the extreme hydrological events have drawn the attention of scientists. The droughts and floods of the Amazon River and its tributaries, with increasing frequency and intensity, are important topics for meteorologists, climate scientists, social sciences researchers, and the civil defense authorities of the Amazon Basin. Climate scientists and meteorologists search for physical reasons for the occurrence of such events to draw schemes to forecast them ever more accurately. [24] studied the extreme droughts in the Amazon Basin and found that such events during cyclic ENSO are coupled with Indian Ocean Dipole modes and Tropical North Atlantic warming. [8] and [25] studied cases of extreme floods and droughts in the region. Modeling studies, e.g., [26] have revealed that deforestation and land surface use can change the regional climate of the basin significantly.

The knowledge of the variability characteristics of hydrometeorological parameters, such as water level on all time scales, is essential both for finding the physical reasons and for forecasting the extreme events. Our results only indicate the possibility of changes in the hydro-climate regime around the mid-1970s.

5. Conclusions

The present study revealed some important characteristics of the variability of the Negro River level at Manaus port. The trend analyses showed that the river level had a slow increasing linear trend since 1902, with a rise of the order of 0.9 m in 122 years. The plots of the annual maxima (flood) and minima (droughts) (**Figure 4**) show that the extremes have become more frequent and more intense since the mid-1970s, as was noted by [2]. The trends in the sets of annual maxima and minima of water level in the past 51 years are found to be stronger compared to the period before the mid-1970s. The annual maximum level (flood) has increased by 0.61 m, and the annual minimum (drought) decreased by 3.57 m; as a result, the annual range (annual maximum minus minimum) has widened by 4.18 m in the last half-century.

The amplitude spectra of the series also revealed important characteristics of the variability of the water level at Manaus port. The spectra are dominated by the seasonal (or annual) cycle, explaining 64% of the total variance of the series (**Figure 8(a)**). The semiannual cycle is responsible for about 3% of the variance. The other important cycles are the 16-year cycle and those in the range of 3 to 6 years. The annual maxima, the minima, and the range series showed the existence of a multi-decadal signal of a 40 to 60-year period (**Figure 6**). The spectra of the maxima are somewhat different from the spectra of the minima. That is, the external forcings that cause variabilities in the maxima (floods) and the minima (droughts) are perhaps distinct. There are indications that the 3 to 6-year cycles affect the intensity of droughts more than the floods.

The series up to the mid-1970s and the later series have shown differences in their spectral characteristics. The annual and semiannual cycles have become more intense in the last half-century than in the period before. These characteristics of the dataset revealed by the trend and spectral analyses indicate the possibility of changes in the hydrological regime after the mid-1970s over one of the main rivers of the Amazon Basin.

The changes found in the trends and in the spectra after the mid-1970s support the hypothesis that the climate regime over the Negro basin has changed.

The quantification of the hydrological extremes in the Negro basin and their intensification in the last half century should be drawn to the attention of the scientists to engage in finding the physical reasons for the phenomena. Floods and droughts affect the lives of the communities in the region, and the government authorities should be briefed with accurate information about the possible occurrence of such phenomena.

Authors' Contributions

The first author was responsible for all stages of the research, data collection, processing, analysis, preparation of results, and writing of the manuscript. The second author was responsible for posing the problem and served as the research supervisor, participating in all stages from conception to the final writing of the manuscript. The third author contributed to the technical review, critical analysis of the content, and improvements to the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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