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Fluvial Dynamics and Hydrological Variability in the Chiriquí Viejo River Basin, Panama: An Assessment of Hydro-Social Sustainability through Advanced Hydrometric Indexes

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Abstract: The objective of this study was to conduct a detailed analysis of the available flow series in the Chiriquí Viejo River basin in Panama. This paper examines the patterns of variation within these series and calculates various hydrological indexes indicative of the region's hydrology. Utilizing advanced hydrological indexes within the Chiriquí Viejo River basin in Panama, which spans an area of 1376 km^2 and supports an estimated population of 100,000 inhabitants, analytical methods were employed to compute indexes such as the Daily Flow Variation Index (QVAR), the Slope of the Flow Duration Curve (R2FDC), the Hydrological Regulation Index (IRH), and the average duration of low (DLQ75) and high (DHQ25) flow pulses. The results indicate moderate flow variability (QVAR of 0.72) and a Hydrological Regulation Index (IRH) of 2.32, signifying a moderate capacity for flow regulation. Notably, low flow events (DLQ75) lasted approximately 3.73 days, while high flow events (DHQ25) lasted around 4.08 days. The study highlights a significant capacity to respond to extreme events, with maximum annual flows reaching 80.25 m^3/s and minimum flows dropping to 3.01 m^3/s. Despite the significant contribution of the basin to hydroelectric power generation and other economic activities, there is an observed need for sustainable management that accommodates hydrological fluctuations and promotes resource conservation. The conclusions indicate that these findings are critical for future planning and conservation strategies in the region, emphasizing the importance of integrating multidisciplinary approaches for Hydro-Social Sustainability. This novel and holistic approach underscores the interdependence between hydrological dynamics, socio-economic activities, and environmental sustainability, aiming to ensure the long-term resilience of the Chiriquí Viejo basin and its communities.

Keywords: Hydro-Social Sustainability; hydrological variability; river basin management; hydroelectric power; flow duration curve; water resource sustainability; hydrological indexes; extreme flow events; climate impact assessment; watershed conservation

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1. Introduction

Water is a universal element that humans use to meet their needs and contribute to development in social, economic, and environmental factors [1]. Water is essential for human health, agriculture, industrial processes, and ecological balance. Although water is indispensable for life, the growth of the global population and the need for continuous economic development have increased pressure on water quality [2]. Globally, there is an urgent need to find sustainable solutions to the growing scarcity of freshwater resources [3].

Hydrological indexes such as QVAR, R2FDC, IRH, DLQ75, and DHQ25 are valuable indicators of water behavior in a basin [4,5]. These indexes allow for the prediction of the likelihood of extreme events and the identification of basins with a higher risk of floods or droughts [6,7]. For instance, DLQ75 and DHQ25 are crucial for estimating the duration and severity of droughts and floods, respectively [8]. Additionally, hydrological indexes can be used to evaluate how climate change may affect the frequency and intensity of extreme hydrological events [9]. That way, they may assist in identifying the most appropriate measures to reduce the risk of extreme events [10].

It has been shown that integrating different indexes increases the accuracy of predictions of extreme events. In this fashion, there is a study where the integration of different hydrological indexes provides a more complete view of the hydrological behavior of a basin, allowing for the improved accuracy of extreme event predictions [11]. These types of analysis allow for obtaining useful information for decision-making, especially in the context of climate change [12]. Additionally, it assesses the vulnerability of different regions to extreme events, enabling the implementation of adaptation and mitigation [13]. Moreover, several studies use indexes as evidence of the effects that changes in hydrology may have on flows. Currently, a variety of indexes are available that can be applied [14].

In the province of Chiriquí, located in the western region of Panama, lies the Chiriquí Viejo River basin, an ecosystem that exemplifies Hydro-Social Sustainability, a new paradigm that merges the management of water resources, community prosperity, and ecological balance. This multidisciplinary approach integrates hydrological dynamics with socio-economic and environmental aspects, aiming to promote sustainable water resource management. Hydro-Social Sustainability advocates for a holistic understanding of water systems, recognizing the interdependence between water, the communities that depend on it, and the ability of these systems to sustain over time.

Hydro-Social Sustainability in the Chiriquí Viejo River basin promotes a holistic understanding of water systems. This includes not only the quantity and quality of available water, but also how local communities use and manage these resources to ensure their future availability. This approach is particularly reflected in the middle basin, where the use of water resources is more extensive. The goal is to ensure that economic activities, such as agriculture and hydroelectric power generation, are conducted in a manner that does not compromise the ecological health of the river and its surroundings.

Despite the importance of the Chiriquí Viejo River basin, there is a lack of relevant information and studies in the field of hydrology that can provide a status of the basin and its sub-basins. To strengthen the effective management of water resources in the Chiriquí Viejo basin, it is essential to address the lack of tools for predicting extreme hydrological events and climate change.

This challenge can be overcome by implementing advanced hydrological indexes, which allow for a detailed characterization of the basin's behavior in response to flow variations and extreme events. In this context, there is a study that highlights the importance of deep learning models in simulating rainfall and runoff, particularly for predicting extreme events where the accuracy of physically based models can be compared to machine learning models [11]. Moreover, research by [12] underscores the critical role of integrating these advanced tools into basin management strategies.

In addition, user-oriented hydrological indexes for early warning systems may be validated through post-event surveys to provide relevant information where extreme hydrological phenomena, such as floods, pose significant challenges for water resource management [12].

On the other hand, the global analysis of extreme hydrological events and their relationship with climate change highlights the need to study the climate-related causes of changes in the hydrological cycle and to develop methods to predict extreme hydrological events at different temporal and spatial scales [13].

This integrated approach not only highlights the regulatory capacity and response of the basin to flow variations, but also emphasizes the interconnection between hydrology, society, and environmental sustainability. By adopting the lens of Hydro-Social Sustainability, this research seeks to establish a framework where hydrological science and sustainability converge, aiming to promote a resilient future for the Chiriquí Viejo basin and its communities.

The measurement of river flows is a crucial component for analyzing the hydrological dynamics of basins, providing essential data for their understanding [15]. However, in vast areas of developing tropical regions, like the Chiriquí Viejo River basin, data availability is often restricted to major river basins [16].

This limitation in public information, which is limited to elementary summaries such as daily average flow, median flow, monthly average, as well as maximum, average, and minimum flow values, can introduce bias in the comprehensive understanding of basin hydrology [17].

The lack of high temporal resolution data limits the ability to understand the short-term hydrological dynamics, which can negatively impact water planning and management, increasing the risk of events such as floods and droughts [18].

The objective of this study is to analyze in detail the available flow series in the Chiriquí Viejo basin, as well as the patterns of variation of the series. Additionally, this work seeks to calculate various hydrological indexes indicative of the region's hydrology. Through this comprehensive analysis, the aim is to provide a deeper understanding of the basin's hydrological behavior, thereby improving the predictions and management of water resources in response to extreme events and flow variations.

The findings of this study are not only crucial for the conservation of local ecosystems and economic infrastructure [19,20], but also offer valuable perspectives that could be applied to similar basins globally [16]. As such, the study contributes to the hydrological knowledge necessary for effective basin management in tropical regions [17].

2. Materials and Methods

2.1. Basin Context

The Chiriquí Viejo basin, located in western Panama, specifically in the province of Chiriquí, has a volcanic topography and a humid tropical climate. This basin supports a population of approximately 100,000 inhabitants [1] and has a climate characterized by temperatures that vary between 20 °C and 25 °C throughout the year. Minimum temperatures can drop to 12 °C and maximum temperatures can reach 30 °C under specific conditions. The basin, covering 1376 km^2, represents an invaluable natural laboratory for hydrological research, given the complexity of its geographical and climatic features.

The basin is significant not only for hydroelectric power generation, which represents 78% of its water allocation, but also for its roles in agriculture, drinking water supply, and industry. However, the basin faces significant challenges, exacerbated by climate change and land use transformation, threatening its sustainability and the water security of the region.

The basin registers an average annual rainfall of 3341 mm, which is unevenly distributed, creating two distinct nuclei: one in the northeastern part with less rainfall (2100–2400 mm) and another in the central part with more rainfall (4000–4800 mm). The length of the basin is 161 km and maintains an average elevation of 1100 m above sea level (m.a.s.l) [1].

The Chiriquí Viejo basin is crucial for hydropower production, agriculture, and drinking water supply. However, it lacks relevant information and work in the field of hydrology. In addition, data on extreme hydrological events, such as floods and droughts, are not available, and need to be identified and measured to fully understand hydrological variability and effectively plan water resources management.

2.2. Selection and Implementation of Hydrological Indexes

To achieve a comprehensive understanding of river dynamics and hydrological variability, we selected hydrological indexes for their recognized utility and applicability.

The choice of these indexes is based on their ability to characterize hydrological data series, both statistically and dynamically, thus reflecting the unique long-term behavior of basins. According to [21], flow indexes derived from time series of flows provide an effective means to characterize hydrological features, facilitating the exploration of processes, the calibration and selection of models, and the classification of basins, especially when limited to flow data [21].

Furthermore, the comparative assessment of hydrological models in large-scale basins, as discussed in the study by [22], underscores the importance of selecting appropriate models to accurately represent daily flow regimes, considering the uncertainties associated with input data, parameters, and model structures [21].

This comprehensive methodology ensures a faithful representation of river hydrology, crucial for the planning and management of water resources in variable environments. The following is a description of the different indexes used in this study:

Daily Flow Variation (QVAR): Calculated as the standard deviation of daily flows divided by the mean daily flow, the QVAR index allows for the assessment of flow variability over time, adapting the methodology to reflect the specific conditions of the basin.

QVAR Index: QVAR is calculated by dividing the standard deviation of daily flows by the mean daily flow. This index provides a measure of the relative variability in the flow over time and is described by Equation (1).

$$\mathrm{QVAR} = \frac{\text{standard deviation}}{\text{Daily average flow}} \tag{1}$$

where
standard deviation represents the standard deviation of daily flow.
Daily average flow is the average daily flow.

Average Daily Flow: it calculates the average of the daily flows throughout the entire recording period. This provides a unique value representing the mean daily flow in the basin for the analyzed period and is described by Equation (2).

$$\text{Average Daily Flow} = \frac{\Sigma_{\mathrm{i}=1}^{\mathrm{n}} \text{Daily Flow i}}{\mathrm{n}} \tag{2}$$

where
$\sum_{\mathrm{i}=1}^{\mathrm{n}}$ Daily Flow i is the sum of daily flows over the period.
n is the total number of observations.

Standard Deviation of Daily Flows: it calculates the standard deviation of daily flows to obtain a measure of the data dispersion around the mean daily flow as it is described in Equation (3).

$$\text{Standard deviation} = \frac{\sqrt{\Sigma_{\mathrm{i}}^{\mathrm{n}} = 1(\text{Average Daily Flow i} - \text{Average Daily Flow})^2}}{\mathrm{n}} \tag{3}$$

where
Average Daily Flow is the flow on day i.
Average Daily Flow is the overall daily average flow calculated for the entire study period
n is the total number of observations or days in the dataset.

Slope of the Flow Duration Curve (R2FDC): the slope of the middle section of the flow duration curve (R2FDC) provides a measure of the basin's capacity to buffer flow variations, incorporating a detailed analysis of identified extreme events. Equation (4) describes how to calculate the R2FDC.

$$\mathrm{p} = \frac{\mathrm{m}}{\mathrm{N}+1} \tag{4}$$

where
m is the ranked order of the flow.
N is the total number of observations.

Calculating Exceedance Frequencies: for each flow value, the frequency at which there is exceedance or equity can be calculated using Equation (5).

$$\text{Excess frequency } (\%) = \left(\frac{\text{Data rank}}{\text{total data} + 1} \right) \times 100 \tag{5}$$

where
Data rank is the position of the flow value in the ordered data series and
total data is the total number of flow observations.

Hydrological Regulation Index (IRH): this index, based on the ratio between the flow volumes during wet and dry periods, provides insight into the basin's capacity to regulate hydrological conditions, facilitating comparison with other studies to ensure standardization and reproducibility. The IRH index is calculated by dividing the flow volume during wet periods by the flow volume during dry periods. This index demonstrates how the basin accumulates and releases water, reflecting its regulatory capacity, and is described in Equation (6).

$$\text{IRH} = \frac{\text{Wet Volume}}{\text{Dry Volume}} \tag{6}$$

where
Wet Volume represents the total volume of flow during wet or rainy periods.
Dry Volume represents the total volume of flow during dry or low rainfall periods.

Calculation of Flow Volumes: one of the first steps in the analysis of this study was to calculate the wet and dry volume, as described below.

Wet Volume Calculation: this calculates the total flow volume during selected wet periods by summing all daily or monthly flow values within these periods as described in Equation (7).

$$\text{Wet Volume} = \sum \text{Wet Flow} \tag{7}$$

where
Wet Flow represents the flow volumes during wet or rainy periods.

Dry Volume Calculation: calculates the total flow volume during selected dry periods by summing all daily or monthly flow values within these periods as described in Equation (8).

$$\text{Dry Volume} = \sum \text{Dry Flow} \tag{8}$$

where
Dry Flow includes all the flow data collected during periods identified as dry.

Identifying the Middle Section: Once the flows have been calculated, the middle section should be identified. The middle section of the FDC typically refers to the portion of the curve between the 33% and 66% exceedance frequencies. This section represents flows that are neither extremely high nor low, and is useful for assessing the basin's capacity to buffer flow variations.

Calculating the Slope (R2FDC): After identifying the middle section, its slope is calculated by using a linear regression method to fit a straight line to the data of the FDC. The slope is calculated by Equation (9):

$$\text{R2FDC} = \Delta\text{y}/\Delta\text{x} \tag{9}$$

where
Δy represents the change in flow values.
Δx is the change in exceedance frequencies corresponding to the middle section of the FDC.

Average Duration of Low (DLQ75) and High (DHQ25) Flow Events: These indexes reflect the basin's response to extreme flow conditions by calculating the average duration of events that exceed established percentiles for low and high flows, respectively.

2.3. Identification of Flow Percentiles

Calculation of Percentiles: Based on the flow data series, the 25th and 75th percentiles are determined. The 25th percentile (Q25) represents the threshold for high flow events, whereas the 75th percentile (Q75) serves as the threshold for low flow events.

$$\text{Q25} = \text{Flow percentile corresponding to 25\% of the data.}$$

$$\text{Q75} = \text{Flow percentile corresponding to 75\% of the data}$$

where
Q25 is the flow percentile corresponding to 25% of the data. This value serves as the threshold for high flow events, meaning 25% of the time, the flow is greater than or equal to Q25.
Q75 is the flow percentile corresponding to 75% of the data. This value serves as the threshold for low flow events, meaning 75% of the time, the flow is greater than or equal to Q75.

Low Flow Events (DLQ75): After Q75 has been determined, there is an identification of all events where the daily flow falls below the Q75 threshold. An "event" begins when the flow drops below Q75 and ends when the flow rises above this threshold again.

High Flow Events (DHQ25): Similarly, after Q25 has been established, all events where the daily flow exceeds the Q25 threshold are identified. An "event" begins when the flow rises above Q25 and ends when it falls below this threshold.

Average Duration of Low Flow Events (DLQ75): Calculate the average duration of all identified low flow events. This involves determining the length of time each low flow event lasts, from when the flow initially drops below the Q75 threshold until it rises above it again as described in Equation (10).

$$\text{DLQ75} = \frac{\sum \text{average duration of all low flow events}}{\text{all number of low flow event}} \tag{10}$$

where the numerator represents the sum of the durations of all events where the flow is less than or equal to the Q75 threshold.

Average Duration of High Flow Events (DHQ25): Calculate the average duration of all identified high flow events. This includes measuring the length of time each high flow event persists from the point the flow exceeds the Q25 threshold until it drops below it as described in Equation (11).

$$\text{DLQ25} = \frac{\sum \text{Duration of each high flow event}}{\text{Total number of high flow events}} \tag{11}$$

where the numerator is the sum of the durations of all events where the flow is greater than or equal to the Q25 threshold.

Analytical Methodology: Data on reception, flow, and other relevant parameters were collected and analyzed using advanced data processing techniques to ensure the accuracy and reliability of the calculated hydrological indexes.

This approach aligns with the findings of [23], who highlighted the utility of advanced machine learning techniques, such as the Cat Boost method, in significantly improving hydrological prediction.

This study underscores how these algorithms can accurately capture the complex dynamics of river systems, which is crucial for effective water resource management. Additionally, the research by [24] supports the integration of deep learning models, such as combining CNN with LSTM and GRU models, to overcome the limitations of singular models in extracting spatiotemporal features. In fact, artificial intelligence has been used to estimate hydrological forecasts for water resource management [25]. Additionally, CNN has been applied together with convolutional-based long short-term memory neural network (ConvLSTM) and backpropagation neural network (BPNN) for a precision agriculture system [26]. Another application in the use of LSTM and GRU showed a significant improvement in its prediction for flood forecasting in Canada [27], while the CNN-LSTM was implemented to predict the streamflow based on 86 stations in the U.S. [28].

These advanced techniques offer a new perspective in interpreting hydrological indexes, particularly in basins with unique characteristics like Chiriquí Viejo, of which the relevance extends to critical sectors such as hydroelectric power generation, agriculture, and drinking water supply.

Comprehensive Hydrological Analysis of the Chiriquí Viejo Basin: The detailed study of the Chiriquí Viejo basin is based on an advanced methodology that utilizes hydrological indexes to deeply understand water dynamics and their implications for resource management and conservation.

These indexes, specifically selected to address particular analytical needs, allow for a thorough assessment of hydrological processes and variability, as well as the impacts of hydroelectric infrastructure in the region. With six hydroelectric plants modulating flow regimes, the methodology captures not only natural variability, but also anthropogenic effects on flow patterns, essential for planning effective responses to extreme fluctuations such as floods and droughts.

The presence of hydroelectric infrastructure in the Chiriquí Viejo basin significantly contributes to renewable energy production, but also presents operational and environmental challenges that impact biodiversity and local communities. Figure 1 shows the location of hydroclimatic stations in the Chiriquí Viejo river basin and its position within the country.

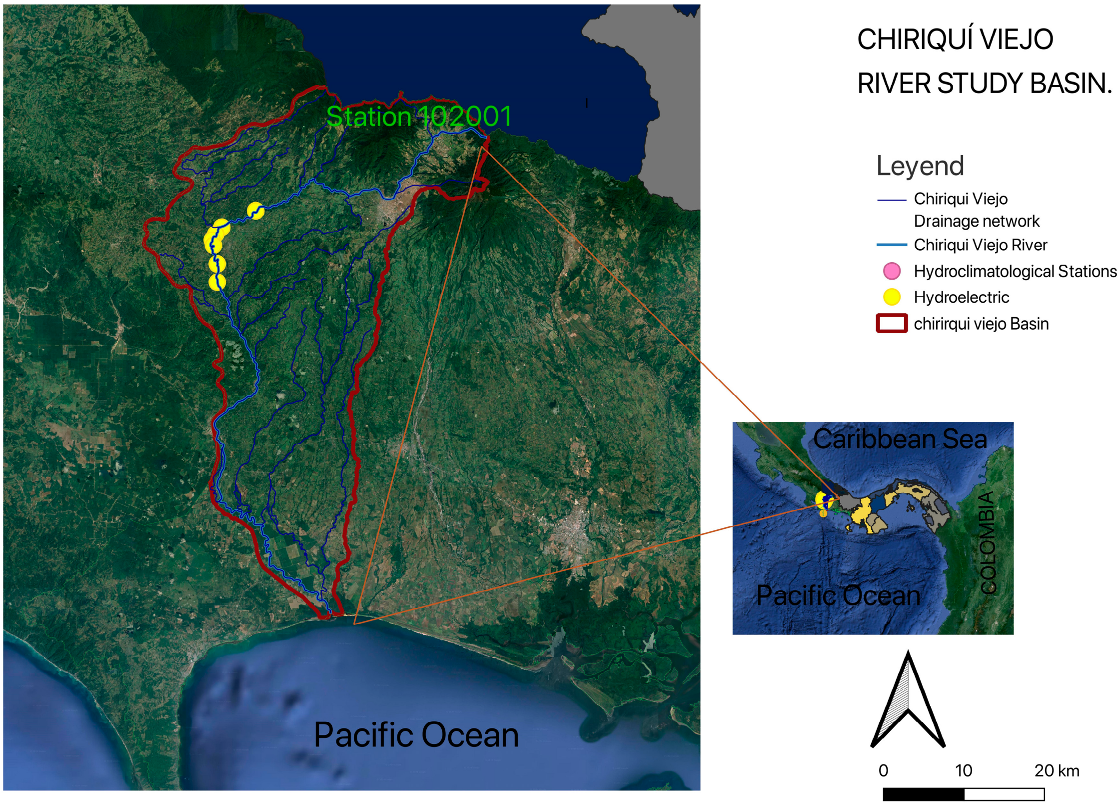

Figure 1. Location of the Chiriquí Viejo River basin and the studied station.

Dataset: The dataset used in this study comes from the Meteorological and Hydrological Institute of Panama, specifically from the Hydrology Department. The daily average flow registered at the hydrological station corresponding to the Chiriquí Viejo river was measured in cubic meters per second (m^3/s) and is located in the Tierras Altas district. This dataset spans the period between 1982 and 2021. The spatial location of the station is at

8°52′0″ N and 82°34′59″ W, marked with the code # 102-001. The information details daily measurements for each month of the corresponding year. This provides comprehensive statistics to be able to analyze variations and hydrological trends in the long term for this specific basin.

Ecosystem Management and Conservation in the Basin: The presence of hydroelectric infrastructure in the Chiriquí Viejo basin significantly contributes to renewable energy production, but also presents operational and environmental challenges that impact biodiversity and local communities. Figure 1 shows the location of hydroclimatic stations in the Chiriquí Viejo river basin and its position within the country.

Reservoir management, by altering natural flows, requires careful handling to protect aquatic ecosystems and ensure water sustainability. This integrated approach reflects a deep understanding of the interaction between hydroelectric infrastructure and basin hydrology, emphasizing the need for balanced management that prioritizes both human development and environmental conservation. Figure 2 depicts the elevation profile of the Chiriquí Viejo River hydroelectric system.

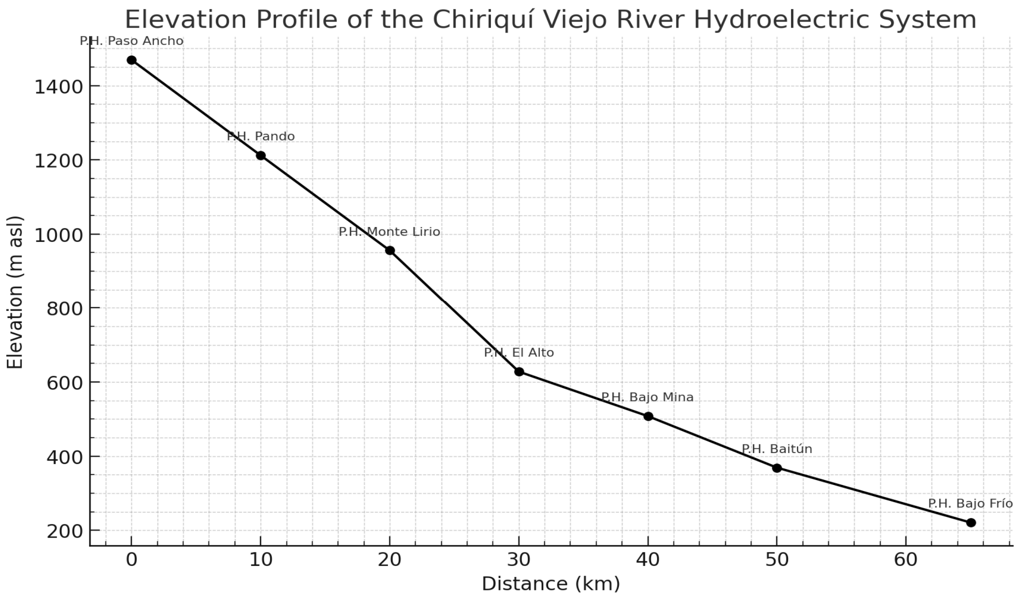

Figure 2. Altitudinal distribution profile of hydroelectric plants along the Chiriquí Viejo River axis.

3. Results

Average Daily Flow: Figure 3 displays the average daily flow in the basin throughout the recording period, which is approximately 7.13 m^3/s. This value represents the average flow on any given day across all recorded years and months.

Standard Deviation of Daily Flows: Figure 4 shows the standard deviation of daily flows, which is approximately 5.14 m^3/s. This indicates the dispersion of flow data around the mean value.

QVAR Index: The QVAR index, shown in Figure 5, is approximately 0.72, indicating that the daily flow variability is 72% of the mean daily flow, suggesting considerable variability in water flow within the basin over time.

3.1. Slope of the Flow Duration Curve (R2FDC)

Flow Duration Curve (R2FDC) Analysis at Station 102001

The Flow Duration Curve (R2FDC) at station 102001 reveals key hydrological patterns crucial for a deep understanding of the behavior of the river system under study.

A notable prevalence of high flow rates is observed in Figure 6, a phenomenon that could be influenced by the specific topography of the basin and sparse vegetation cover, facilitating a rapid surface runoff response to episodes of intense rainfall, particularly noticeable around the 20% exceedance threshold. Moreover, the difference in slopes of the R2FDC before and after this inflection point denotes a varied sensitivity to changes in exceedance percentage, indicating that higher flows are particularly vulnerable to minor fluctuations in hydrological conditions, which could trigger significant adjustments in the magnitude of these flows.

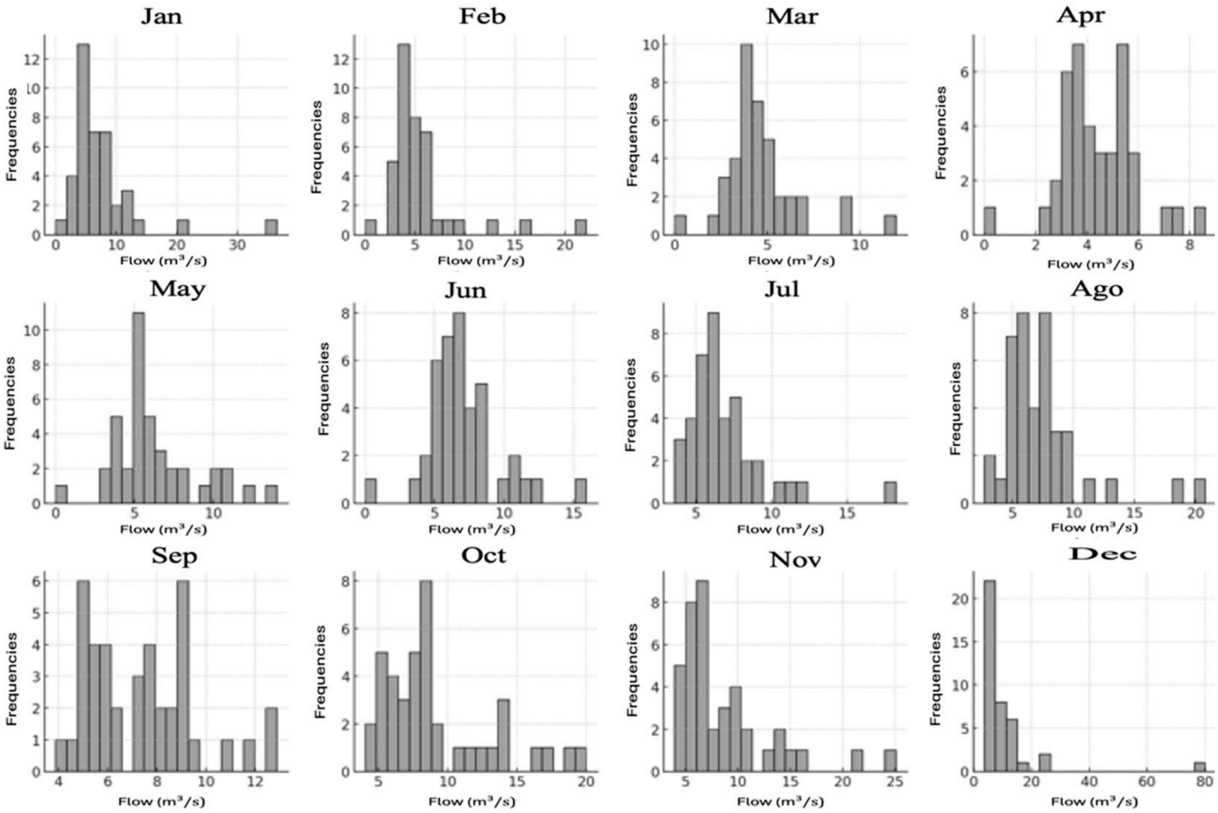

Figure 3. Boxplot of average flow by month.

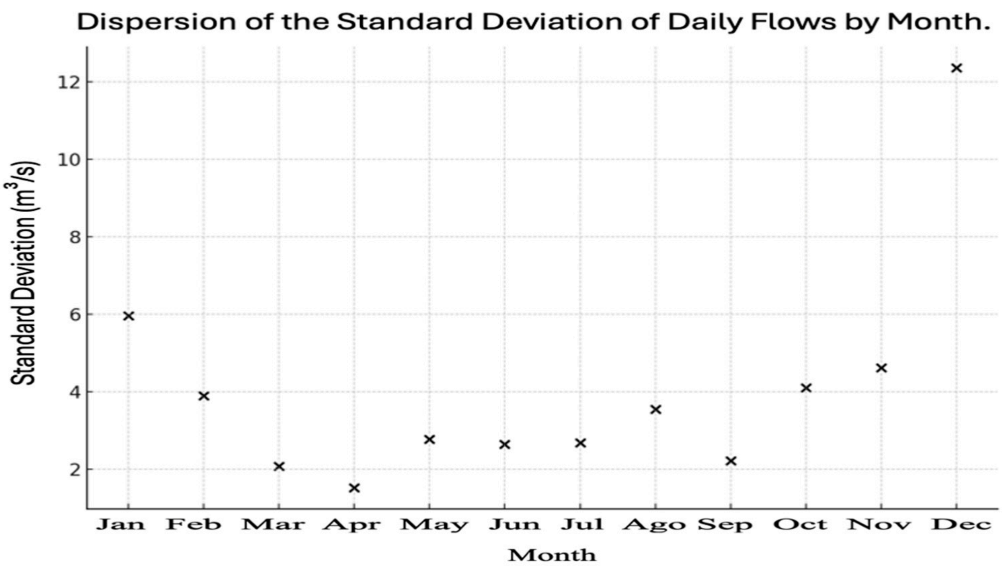

Figure 4. Standard deviation of daily flows.

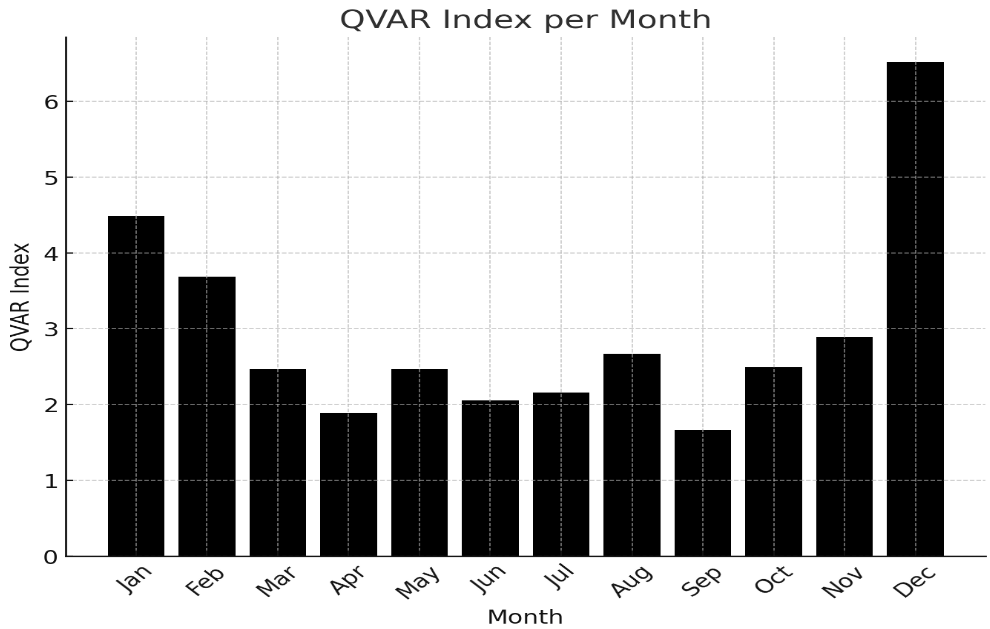

Figure 5. QVAR index by month.

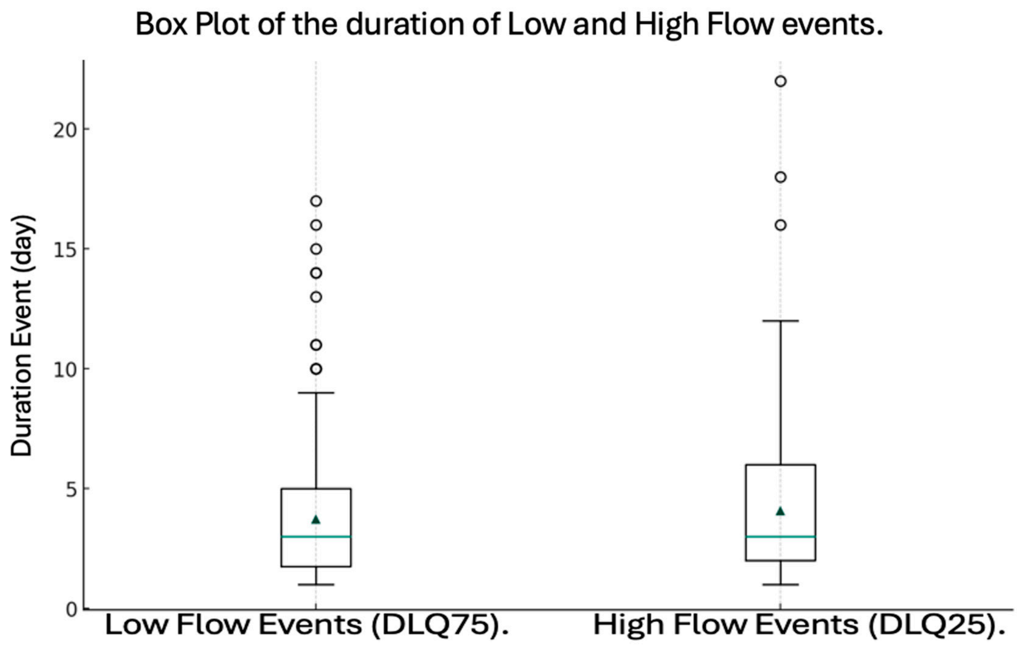

Figure 6. Flow duration curve (R2FDC).

The year 2020 stands out in the hydrological record, with an annual maximum flow of 80.25 m^3/s and notable variations extending to a minimum flow of 3.01 m^3/s in 2021, illustrating the high variability of the system, evidenced by a variation coefficient of 0.82.

This period is not only marked by its hydrological extremes, but also by its association with severe weather events, particularly hurricanes Eta and Iota in November 2020, underscoring the impact of extreme meteorological phenomena on river dynamics.

Hydrological Regulation Index (IRH):

The Chiriquí Viejo basin, characterized by a Hydrological Regulation Index (IRH) of 2.32 shown in Figure 7, exhibits a moderate capacity to regulate its flows, attenuating hydrological fluctuations throughout the year and thereby mitigating the risk of both floods and droughts. This moderation is most notable during the rainy season, with an increase in the system's regulatory capacity, while during the dry season, this capacity decreases, highlighting the importance of adaptive water management that addresses the basin's inherent seasonal variability.

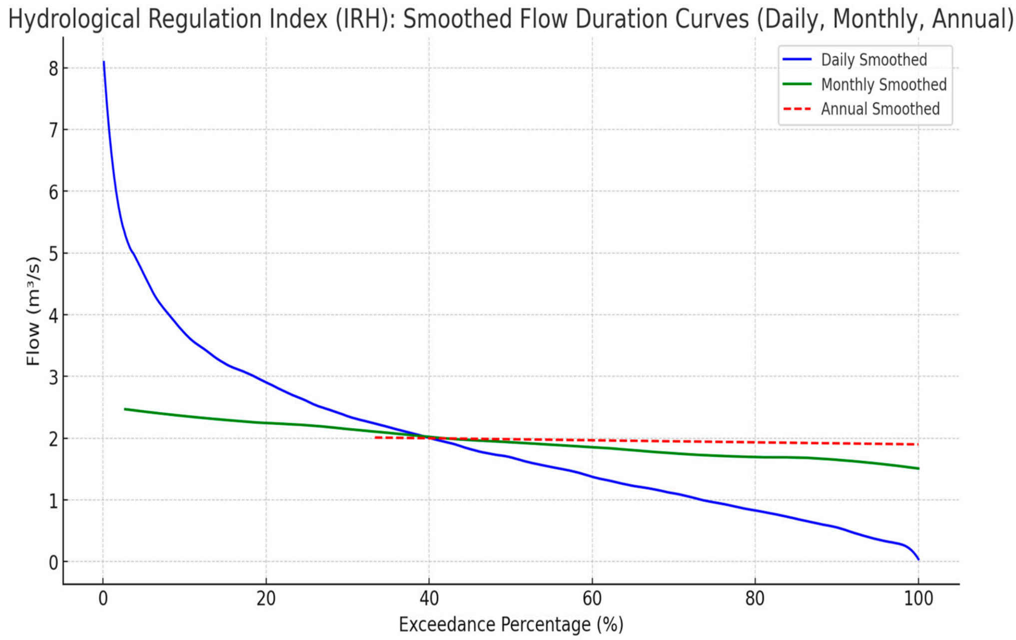

Figure 7. Typical curves of daily, monthly, and annual flow durations.

The landscape of hydrological regulation is further complicated when considering the spatial heterogeneity within the basin, which shows a higher IRH in mountainous areas and lower in plain areas.

This spatial distribution of the IRH invites a more nuanced understanding of hydrological regulatory capacity and suggests the need for water management and planning strategies that recognize and adapt to both temporal and spatial variations. Detailed research is essential to delve deeper into the basin's dynamics, integrating the IRH with additional variables such as precipitation, evapotranspiration, and vegetation cover for an accurate and holistic interpretation.

The Chiriquí Viejo basin reflects the complex dynamics faced by many river systems in the era of climate change. With an IRH indicating a moderate regulatory capacity, it is imperative that water resource managers and infrastructure designers consider the variability of the IRH and its implications for water management.

Ensuring the availability of water resources and reducing vulnerability to extreme events will depend on strategies that address not only annual and seasonal fluctuations, but also the spatial particularities of the basin.

Average Duration of Low (DLQ75) and High (DHQ25) Flow Events:

On average, low flow events (DLQ75) last about 3.73 days, implying that events where the flow is below the 75th percentile last around this time before rising again above that threshold as shown in Figure 8. Conversely, high flow events (DHQ25) last approximately 4.08 days, indicating that events where the flow exceeds the 25th percentile typically last this duration before falling below the threshold again.

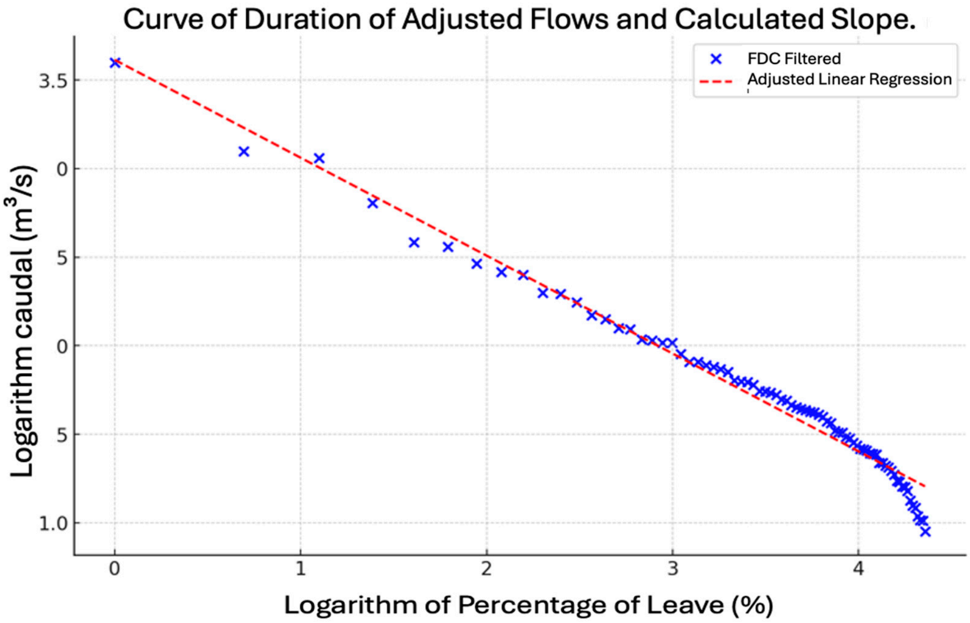

Figure 8. Diagram of low and high flow event durations.

4. Discussion

The assessment of hydrological variability in the Chiriquí Viejo basin, evidenced by indexes such as QVAR (0.67) and IRH (2.32), reveals a complex behavior dominated by seasonality and extreme events. This high variation in flow, combined with the basin's moderate regulation capacity, poses challenges for sustainable water management. Similarly, these findings resonate with previous studies, such as that by [29], who emphasize the importance of adaptive strategies in the face of climatic variability. Likewise, Ref. [30] highlight the delicate balance between hydroelectric power generation and ecological conservation in river basins.

Consequently, the hydrological variability of the Chiriquí Viejo basin directly impacts Hydro-Social Sustainability. The limitation in water availability during the dry season contrasts with vulnerability to flooding during the rainy season. This situation complicates the planning and efficient use of water for human consumption, agriculture, and energy generation. Therefore, the development of sustainable management strategies must consider adaptation to natural variability, minimization of anthropogenic impacts such as infrastructure construction, promotion of equitable resource use, and strengthening of institutional capacity for water management.

Finally, the advanced hydrometric indexes used in this study [31], combined with integration with previous research [32], constitute valuable tools for the sustainable management of the Chiriquí Viejo basin. An adaptive approach that considers hydrological variability and the needs of the various water user sectors will ensure its sustainable use in the long term as it has been proposed for the water management in the Poqueira River in Southern Spain [33]. This can also be observed in the analysis performed for the Yangtze River where there were some recommendations to mitigate the negative effects in the ecosystem due to the presence of the Three Gorges Dam [34].

5. Conclusions

The thorough examination of the Chiriquí Viejo River basin through the lens of Hydro-Social Sustainability reveals a mosaic of numerical data that highlight both the vitality and vulnerability of this system.

The Hydrological Regulation Index (IRH) yields a value of 2.32, which not only underscores a moderate capacity for flow regulation that mitigates annual fluctuations, but also points to the need for bolstering water management strategies in response to evident seasonality.

Seasonal variability is reflected in the specific extreme flow figures: in 2020, the basin experienced a maximum annual flow of 80.25 m^3/s, in stark contrast to the minimum flow of 3.01 m^3/s observed in 2021. This spectrum of extremes, captured by a coefficient of variation of 0.82, demonstrates the pronounced dynamics of flows and the urgent need to manage water resources in an adaptable and proactive manner.

Adding complexity to this management, the analysis reveals that the average duration of low flow events (DLQ75) is approximately 3.73 days, while for high flow events (DHQ25), the average duration is 4.08 days.

These metrics emphasize the basin's response to extreme conditions and their impact on infrastructure planning and conservation strategies.

The analytical approach adopted reveals a multifaceted interaction between the IRH and other hydrological indexes and, when viewed through the prism of severe phenomena such as hurricanes Eta and Iota, highlights the interconnectedness between river systems and meteorological forces.

This link between hydrological variability and extreme weather events underscores the relevance of the multidisciplinary and holistic approach to Hydro-Social Sustainability.

The conclusions of the study transcend the Chiriquí Viejo basin, providing lessons applicable to other tropical regions. Water management, imbued with numerical data and a socio ecological context, must advocate for sustainability and resilience, balancing the need for ecological preservation with economic viability.

The results of this study indicate that improving long-term sustainability requires the implementation of adaptable and innovative solutions. Specifically, the analysis highlights the need for infrastructure that can respond effectively to natural and anthropogenic variations within the basin. This approach is essential to maintain water security in the face of the challenges posed by a changing global climate.

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