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Trends in Flow Intermittency, Variability, and Seasonality for Taiwan Rivers

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Abstract: In Taiwan, rivers have steep slopes and short lengths, making it difficult to retain water in the rivers. Therefore, understanding the flow characteristics is essential. This study analyzes data from 65 flow stations with over 30 years of records to characterize the annual mean number of low-flow days, flow variability, and the seasonality of low-flow occurrences. The analysis uses indices such as the intermittency ratio, Richards–Baker flashiness index, and six-month seasonality of the dry period (SD6) and evaluates trends in these indices using the Mann–Kendall test. The results show that nearly 70% of the stations have an intermittency ratio of less than 0.1, although the number of low-flow days has significantly increased over time. Stations in the southwestern watersheds exhibit higher flow variability; however, the trends in flow variability are not statistically significant. Low-flow events predominantly occur during the dry season, with 68% of the stations experiencing them between January and March. The findings on flow characteristics and their long-term trends provide references for river management and water resource planning in the future.

Keywords: Taiwan rivers; intermittency ratio; seasonality; Richards–Baker flashiness index; Mann–Kendall test

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Academic Editors: Leszek Sobkowiak and Dariusz Wrzesiński

Received: 21 December 2024
Revised: 16 January 2025
Accepted: 17 January 2025
Published: 18 January 2025

Citation: Chen, H.-Y.; Fang, X.; Yeh, H.-F. Trends in Flow Intermittency, Variability, and Seasonality for Taiwan Rivers. *Water* **2025**, *17*, 271. https://doi.org/10.3390/w17020271

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1. Introduction

Global warming has caused gradual climate anomalies. According to the Intergovernmental Panel on Climate Change (IPCC) 2023 Climate Change Synthesis Report [1], since the 1950s, the proportion of the world experiencing extreme climate conditions, such as repeated occurrences of floods, heatwaves, droughts or storms at the same time has gradually increased. These extreme climate states have been influenced by a combination of climatic changes, human activities, and other non-climatic factors. Taiwan is characterized by a long north–south orientation and a narrow east–west width, with the Central Mountain Range serving as the main divide. Most rivers flow in an east–west direction and the mountain slopes are steep. Consequently, these rivers are short and steep, and, during heavy rainfall, their turbulent flows carry large amounts of sediment. The flow rates of the rivers rise and fall rapidly in response to the precipitation, making water storage challenging [2]. Given the characteristics of rivers in Taiwan that make water storage difficult, it is important to identify appropriate indicators to analyze and understand river behavior. Intermittency, variability, and seasonality are three important behavioral characteristics of rivers. The intermittency cycle is critical for water management. It refers to an increase in intermittency, which indicates a decline in groundwater levels and reduced runoff [3]. Additionally, the species richness of different aquatic communities decreases with increasing intermittency, and flow variation has a greater impact on aquatic animal

groups than pollutants [4–6]. These river characteristics may alter by climate change [7,8]. Understanding these characteristics is essential for achieving ecological protection and effective river management [9,10].

Intermittency is defined as a river that is non-perennial, with periodic or non-periodic river breaks, and is used to describe the state of the river [3,8,11–14]. Some studies have used intermittency as an indicator of river classification, but there is no consistent value for the classification. For example, Sauquet et al. [13] defined the number of no-flow days as the number of days with observed daily flow <1 L/s. Rivers were considered intermittent when the mean no-flow days were ≥5 days/year, rivers with mean no-flow days <5 days/year were regarded as weakly intermittent, and other rivers were considered perennial; Belemtougri et al. [11] used the mean number of dry months per year as a flow index to assess intermittency and classified rivers as follows: rivers with a mean number of dry months of 0–1 are considered to be perennial, maintaining flow more than 90% of the time; rivers with 2–4 dry months were considered weakly intermittent, with stagnant and isolated pools during the dry season; rivers with 5–7 dry months were considered highly intermittent, with a lack of surface water during the dry season; and rivers with 8–12 dry months were considered ephemeral, flowing only in direct response to precipitation events. Reynolds et al. [8] and Yu et al. [15] quantified intermittency with the mean number of zero-flow days per year and the percentage of months that were below threshold across the entire record, respectively. It shows that intermittency is easily influenced by regional factors. Therefore, we consider river intermittency as a broad description of the hydrological state and need for the regional analysis of river intermittency.

Low flow is a seasonal phenomenon and an integral component of the flow regime of any river. Intermittent and ephemeral flows characterized by naturally prolonged cycles of zero flow, which is often considered to be the lower limit of low flow in hydrology [16]. A reduction in flow may cause a river to change from a perennial to an intermittent river due to climate change, which can significantly impact human water use and ecosystems [8]. In the USA, the most widely used indices are the lowest average flows that occur for a consecutive 7-day period at the recurrence intervals of different years as the low-flow threshold [16–18] and expressed it as q7. When the river flow drops below q7, it may result in adverse impacts or even damage to the river and its surrounding ecosystems. Poshtiri et al. [17] mentioned that the q7 of the 10-year return period is widely used in practical applications and designs. In Taiwan, the 10-year return period rainfall is often used as a reference for the designing of regional drainage systems and basic flood prevention infrastructure [19]. However, the 10-year return period represents the average interval between occurrences of similar events and does not guarantee that such events occur precisely once every 10 years. Additionally, with climate change leading to increasingly extreme conditions, the 10-year return period may no longer be reliable in the future. Therefore, this study adopts the annual average q7 as the low-flow threshold to analyze the frequency of low-flow occurrences in rivers.

The amount of flow variability is primarily used to describe the fluctuation of river flows. Studies on flow variability [12,20,21] have been analyzed using the Richards–Baker Flashiness (RBF) index developed by Baker et al. [22]. Wray et al. [23] referred to the RBF index as a measure of flow uniformity and as a function of land use and precipitation characteristics. Although the coefficient of variation [24] or the standard deviation of daily streamflow can also quantify flow variability, the RBF index can account for variations in the time series by considering the differences between consecutive time points. Unlike metrics such as the coefficient of variation, which treats each streamflow data point as a non- consecutive value, the RBF index is better suited for evaluating short-term variability in streamflow time series. Therefore, the RBF index was selected as an indicator to describe the river flow properties.

Seasonality is primarily used to describe the dates on which river flow events occur and can also serve as an indicator for regional delineation [12–14,24–26]. Sauquet et al. [13] noted that flow intermittency is strongly influenced by seasonality, which varies significantly across countries. This suggests that seasonality is also an important indicator of streamflow events in Taiwan. The Six-month Seasonality of Dry periods (SD6) is an analytical method proposed by Gallart et al. [25] to assess the concentration of flow events during the dry or wet seasons of individual regions. SD6 not only classifies river seasonality similarly to the seasonality ratio (SR) [26], but also further determines the timing of the occurrence of flow events. SD6 has been utilized for flow event analyses [12,27]. Therefore, we selected SD6 for analysis seasonality. In this study, the wet and dry seasons of rainfall in Taiwan were considered, with the year divided into the wet season from May to October and the dry season from November to April of the following year. Additionally, the directional statistic method [24] was applied to convert the dates of flow events into directional angles. The dates of concentrated flow events were then counted, and the lengths of the vectors were used to present the regularity of the flow event timing. This approach helped analyze the actual months of flow event occurrence and difference.

Intermittency, variability, and seasonality are three critical behavioral characteristics of rivers that enable a more comprehensive understanding of river dynamics—essential for water resource management, ecosystem protection, and drought adaptation [8,28]. However, these characteristics have not been fully evaluated in Taiwan. In addition, studies on intermittency are primarily focused on continental or Mediterranean climate regions [11,29], with limited evaluation in monsoon climate regions like that of Taiwan. To fill this gap, this study aims to comprehensively analyze three key river characteristics—intermittency, variability, and seasonality: (i) To quantify three characteristics, the intermittency ratio (IR) is used to measure the percentage of low-flow days, representing river intermittency; the Richards–Baker Flashiness Index is applied to assess the degree of flow variability; and the directional statistics combined with the Seasonality of 6 Months in the Dry Season (SD6) is used to characterize seasonal patterns and the concentration of low-flow events. (ii) We aim to understand the long-term temporal variation in these indices. (iii) We aim to investigate the spatial distribution of these indices across Taiwan. This study not only advances the understanding of river behavior in monsoon climates but also provides vital information for riverine ecosystems sustainably and managing water resources in Taiwan.

2. Materials and Methods

2.1. Study Area and Dataset

According to the Water Resources Agency [2], geographically, Taiwan has a total area of about 36,000 km^2 and is located at the boundary between the Eurasian Plate and the Philippine Sea Plate. The Tropic of Cancer crosses through Taiwan, which has a subtropical climate affected by monsoons, with a humid and rainy climate and an average annual total rainfall of about 2500 mm. The climate is affected by its location in the western Pacific Ocean and the topography of the region, resulting in an uneven temporal and spatial distribution of precipitation. Rainfall predominantly occurs during the plum rainy season from May to July and the typhoon season from July to September. Dry conditions occur in the spring during the alternation of the northeast and southwest monsoon. During the dry season (November to April), river flows are extremely low, constituting only 23.8% of the average annual total runoff, and rivers may even experience periods of desiccation.

Topographically, Taiwan is long from north to south and narrow from east to west. Mountainous areas above 1000 m in elevation account for 32% of the island, while hills between 100 and 1000 m account for 31%, and alluvial plains below 100 m account for 37% of the island's area, where the population, agriculture, and industry are concentrated.

Taiwan's rivers, with the Central Mountain Range as the main river divide, predominantly flow east or west, towards the Taiwan Strait and the Pacific Ocean, respectively. The rivers are short and steep, with turbulent flows that carry large amounts of sediment during heavy rainfall. River flow fluctuates rapidly with the rainfall. Due to the steep slopes and short rivers lengths, water storage in these rivers is challenging. Although Taiwan receives abundant precipitation, its distribution is uneven, both temporal and spatial, varying significantly with the seasons.

Considering the temporal and spatial distribution of rivers in Taiwan for trend analysis, we need the long-term flow data from the river gauges. We chose 65 stations with at least 30 years of data between 1960 and 2022, and the locations and characteristics of these stations are shown in Figure 1 and Table S1. Additionally, this study downloaded the 2018 version of the 20 m grid digital terrain model (DTM) data for Taiwan areas, provided by the Department of Land Administration from the Government Information Open Platform for analysis.

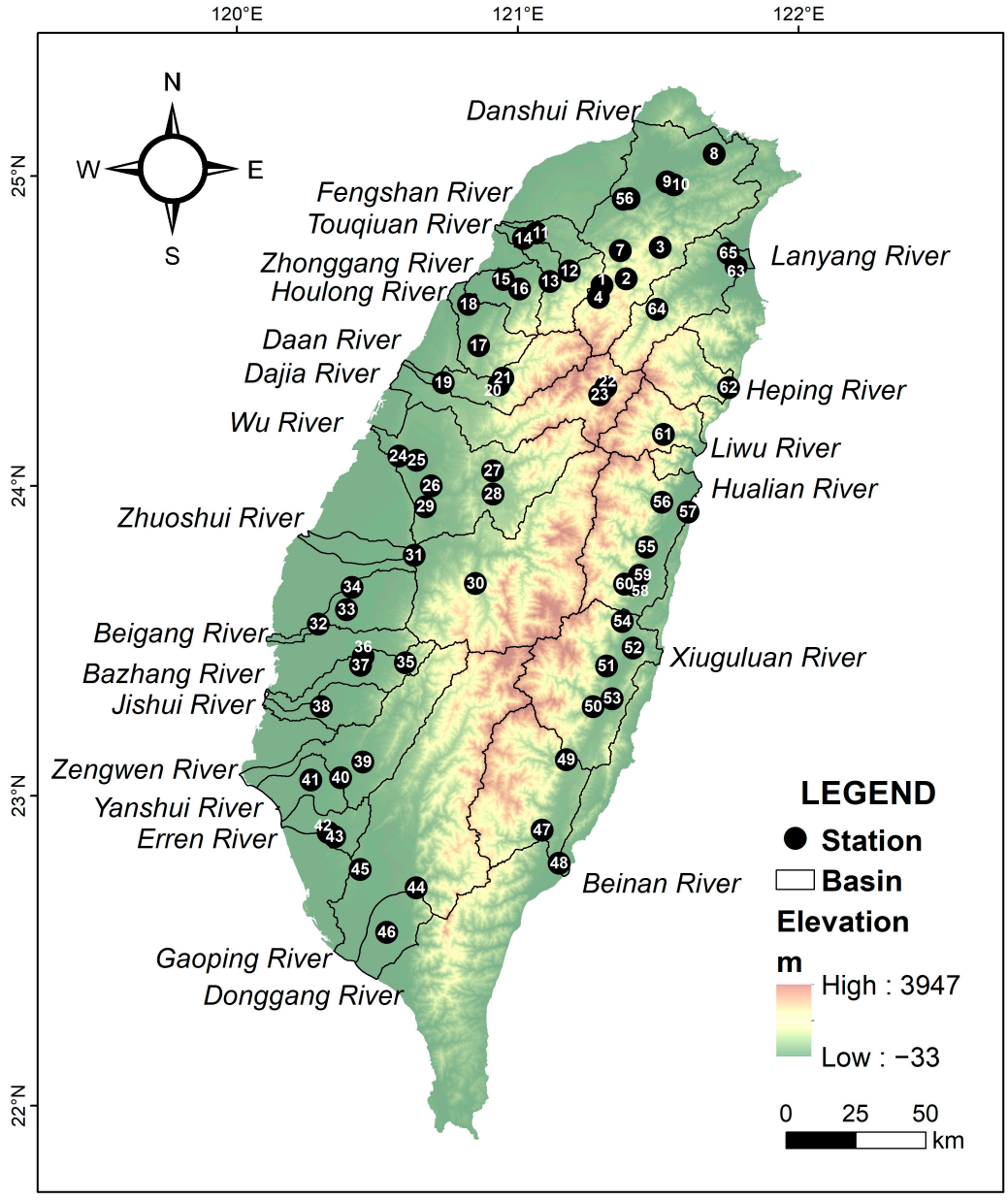

Figure 1. Map of 65 stations and basins in Taiwan. The numbers represent stations' no.; detailed information can be found in Table S1.

2.2. Flow Intermittency

Flow intermittency refers to the percentage of days when low flow occurs in the catchment and as indicated by the intermittency ratio (IR) of Yildirim and Aksoy [3]:

$$\mathrm{IR} = \frac{n_{dry}}{N} \tag{1}$$

where n_{dry} is the number of days per year when the flow is below the threshold, N is the total number of days in a year (usually 365 days; in leap year, it is 366 days). The IR is the percentage of days with average annual low flow.

The low-flow threshold is q7, the lowest average flows that occur for a consecutive 7-day period at the recurrence intervals of different years [16–18]. When the river flow drops below q7, it may result in adverse impacts or even damage to the river and its surrounding ecosystems. This study quantified intermittency using the IR with low-flow thresholds and a daily scale, offering a finer temporal resolution compared to a monthly scale. Unlike methods that use zero as the threshold, this approach provides greater adaptability to different climatic conditions.

2.3. Flow Variability

In this study, the Richards–Baker Flashiness index (RBF) developed by Baker et al. [22] was used as an indicator of flow variability:

$$\mathrm{RBF} = \frac{\sum_{i=1}^{n} |q_{i-1} - q_i|}{\sum_{i=1}^{n} q_i} \tag{2}$$

The RBF index is calculated by summing the absolute value of the variance between the daily flow (q_i) and the previous day's flow (q_{i-1}) and dividing by the sum of the daily flows for each year. The RBF index increases as the river flow becomes more variable, with a theoretical maximum value of 2 [21], for example, when a river's flow generated by recharge is rapidly discharged and stops flowing within a day, only to resume upon the next recharge event, leading to daily flow variations twice the total flow. This scenario is likely to occur in ephemeral streams, which flow only during rainfall events. An RBF index of 0 indicates a stable river flow with no variation.

2.4. Seasonality

The flow seasonality index used in this study is expressed as Six-month Seasonality of Dry periods (SD6), proposed by Gallart et al. [26]:

$$\mathrm{SD6} = 1 - \left(\frac{\sum_{1}^{6} Fd_i}{\sum_{1}^{6} Fd_j} \right) \tag{3}$$

Fd is the multi-year frequency of low-flow months, i refers to six consecutive wet months in a year, and j refers to the remaining six dry months.

In this study, the months from May to October of each year are considered the wet season, while the months from November to April of the following year are considered the dry season. Theoretically, when the absolute value of SD6 is close to 1, it indicates that the flow is seasonal, while an absolute value of SD6 is close to 0 means that the flow is not affected by seasonality. A value of SD6 greater than 0 indicates that low flows occur during the dry season, while a value of SD6 less than 0 indicates that low flows occur in the wet season.

To identify the month in which low flow most frequently occurs, this study used directional statistics based on previous research [25,27,28]. The dates of low flow occurrences at

each station were converted into vector angular values to identify the main occurrence date of low flow, as described below. The following formulas are used for direction statistics:

$$\theta_i = (Julian\ day)_i \left(\frac{2\pi}{365}\right) \tag{4}$$

$$x_i = \sin\theta_i,\ i = 1, 2, \cdots, n \tag{5a}$$

$$y_i = \cos\theta_i,\ i = 1, 2, \cdots, n \tag{5b}$$

$$\text{median}(\theta) = \tan^{-1}\left(\frac{\text{median}(x)}{\text{median}(y)}\right) \tag{6}$$

$$\text{MD} = \frac{365}{2\pi}\text{median}(\theta) \tag{7}$$

$$r = \sqrt{x^2 + y^2} \tag{8}$$

In this study, dates were converted to angular values to avoid computational issues related to leap year. Specifically, *Julian day* represents the date of the low flow event, which is converted to the day of the year. For example, 1 January is day 1; 2 January is day 2; 1 February is day 32, and so on. θ_i is the angular value (in radians) of low-flow day i. The denominator is increased by 1 when a leap year is encountered.

For a single station with data for n low flow dates, median(x) and median(y) are the coordinates of the median low-flow date and are located in the unit circle. To make the initial point (θ_0= 0) coordinate at (x, y) = (0, 1) and rotate it clockwise, let x = sin(θ), y = cos(θ); median(θ) is the median direction of the low-flow date to avoid the effect of extreme values; MD is the median date, converting the median direction back to a day of the year, with the expectation that watersheds with similar MD values may exhibit similarities in other important hydrological features; median(r) is the distance between the x-y coordinates of the median date and the center of the circle ($0 \leq r \leq 1$), representing the regularity of the median date for the low-flow occurrence. When median(r) is close to 1, it indicates that all low-flow events at the station occurred on the same day of the year, while, when median(r) is near 0, it indicates that low-flow events in the watershed were more variable in date and more widely dispersed around the mean date. This approach provides a measure of the distribution of the data in non-dimensional units.

2.5. Trend Analysis

The Mann–Kendall [30,31] test and Sen's slope [32] are statistical methods widely applied in hydrology to analyze trends in time series data. In this study, the Mann–Kendall test and Sen's slope estimator were applied to calculate the magnitude of the trend for the IR, RBF index, and SD6.

The Mann–Kendall test is a non-parametric statistical test that is commonly used to determine the trend of time series data. Assuming that there is a time series $T = \{t_1, t_2, \cdots, t_n\}$ with data $X = \{x_1, x_2, \cdots, x_n\}$, the statistic ($S$) of the Mann–Kendall test is calculated as Equation (9). When S is positive means the trend is positive; when S is negative means the trend is negative.

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} \text{sgn}(x_j - x_k), \text{sgn}(x_j - x_k) = \begin{cases} +1,\ x_j - x_k > 0 \\ 0,\ x_j - x_k = 0 \\ -1,\ x_j - x_k < 0 \end{cases} \tag{9}$$

When $n \geq 10$, the Mann–Kendall test statistic S is approximately normally distributed and has a mean value of 0. The variance is the following:

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{10}$$

The Z value is obtained from S under different conditions and can be used to determine whether the time series data have a significant trend or not, which is defined as shown in Equation (11). When $|Z| \geq Z_{\alpha/2}$, the time series data have a significant trend. The significance level α is the threshold for determining statistical significance, and different significance levels correspond to different $Z_{\alpha/2}$ thresholds for recognizing a significant trend.

$$Z = \begin{cases} \frac{S+1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S-1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \tag{11}$$

In this study, the significance level α is set at 0.05, indicating that a trend is considered significant if the p-value $\leq \alpha$. The Mann–Kendall test is a two-tailed test, so the critical $Z_{\alpha/2}$ value for a 0.05 significance level is 1.960. If $|Z| \geq 1.960$, the time series is considered to have a significant trend. Conversely, if $|Z| < 1.960$, the trend is not statistically significant.

The Sen's slope estimator is a non-parametric statistical as well. It determines the trend slope (β) of a time series by calculating the median of the slopes between all possible pairs of data points in the series. The formula for calculating β is as follows:

$$\beta = median\left(\frac{x_j - x_k}{j - k}\right) \tag{12}$$

where x_j and x_k are the data values of time series at times j and k ($j > k$), respectively, j = 1 to $n - 1$, and k = 2 to n. The slope β differs from the slope obtained through linear regression because it is based on the median value, making it robust against the influence of outliers in the data sequence. When the slope β is positive, it indicates an increasing trend in the data series. Conversely, when β is negative, it signifies a decreasing trend in the data series.

3. Results

3.1. Flow Intermittency

In this study, the intermittency ratio (IR) was used as an indicator of flow intermittency, and the analysis results are shown in Figure 2A. For Taiwan, the mean IR of 65 stations is 0.11, indicating that the annual average number of low-flow days across all stations is 40 days. Among these stations, 23.1% have IR values between 0.10 and 0.20, meaning that the annual average number of low-flow days for these 15 stations ranges from 36.5 to 73.5 days. Additionally, 69.2% of the stations have an IR less than 0.10, indicating that 45 stations experience low flow for less than 10% of the year. In conclusion, nearly 70% of the stations in Taiwan rivers where non-low-flow days account for 90% per year, which can be regarded as perennial rivers.

3.2. Flow Variability

In this study, the Richards–Baker Flashiness Index (RBF) was used to assess the variability of river flow in Taiwan, and the results of the analysis are shown in Figure 2B. The analysis shows that the RBF values for all the stations in Taiwan are below 1, with an average of 0.41. The RBF index ranges from 0 to 2, where higher values indicate greater flow variability [18]. Based on these criteria, river flow variability in Taiwan is relatively low.

The orange and red points in Figure 2B represent stations with RBF values greater than 0.6, totaling 11 stations, which account for 16.9% of all stations in Taiwan. These stations are primarily concentrated in the southwestern region, with nine stations, followed by the northwestern region, with two stations. The higher RBF values at these stations are mainly caused by extreme rainfall events associated with typhoons. Additionally, the average RBF is 0.29 for stations in mountainous areas with average catchment elevations above 1000 m upstream of the station, 0.52 for stations in hilly areas with elevations between 100 and 1000 m, and 0.78 for stations in plain areas with elevations below 100 m. This suggests that RBF values may be affected by topography.

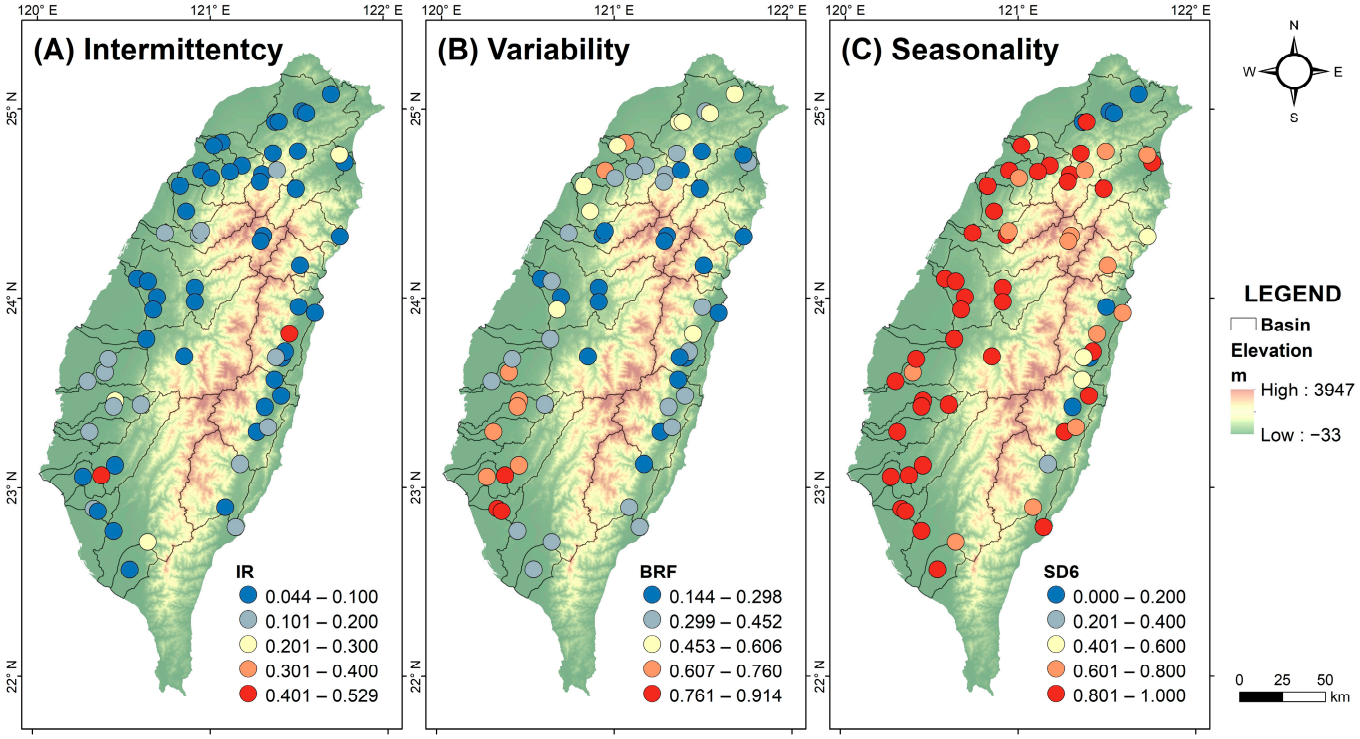

Figure 2. Spatial distribution of 3 indices: (**A**) IR; (**B**) RBF; and (**C**) SD6.

3.3. Low-Flow Seasonal

In this study, SD6 was used as an indicator of the concentration of low-flow events. It is known that, when SD6 = 0, low-flow events are not affected by the seasonality, and, when SD6 is close to 1, it indicates that the low-flow events are concentrated in the dry season from November to following April. As shown in Figure 2C, the results reveal that the average SD6 of all the river stations in Taiwan was 0.76, and 89% of the stations had SD6 > 0, meaning that low-flow events in Taiwan rivers are predominantly concentrated in the dry season.

As shown in Figure 3 and Table 1, the directional statistics revealed that 44 stations, accounting for 68% of the total number of stations in Taiwan, had low flow concentrated from January to March, which spans the transition from winter to spring. The SD6 at the stations west of the Central Mountain Range are relatively high, as shown in Figure 2C. The results suggest that the low-flow events at these stations tend to occur during fixed periods, highlighting a key period for management attention.

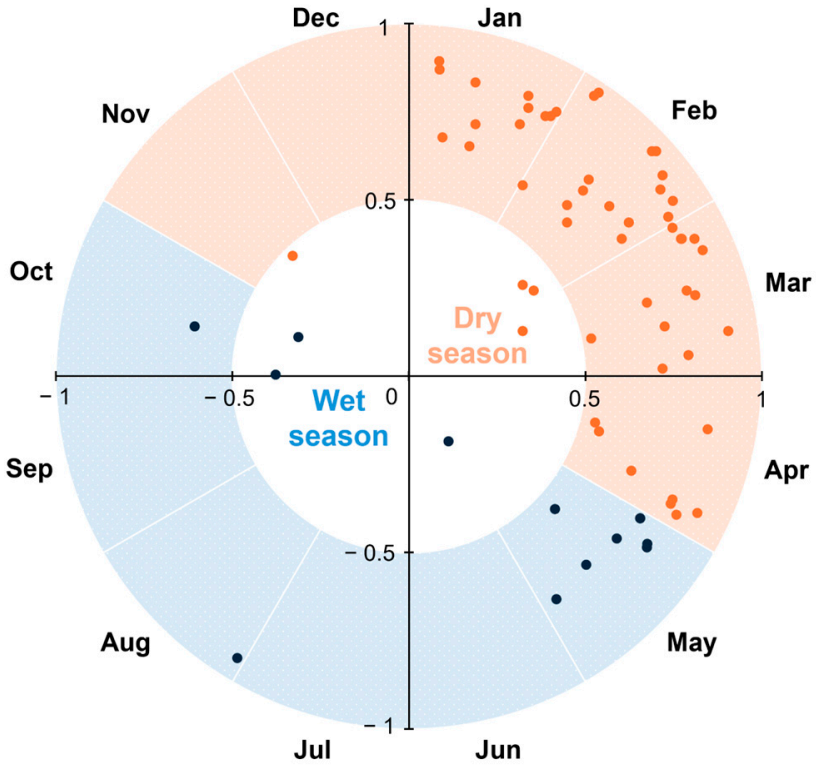

Figure 3. Median occurrence of low-flow days at 65 gauging stations from 1960 to 2022. Median date (MD is converting the median direction back to a day of the year) and regularity (median(*r*) is distance between the x-y coordinates of the median date and the center of the circle) of low-flow occurrence.

Table 1. Number of stations in the month when low flow occurs.

Low Flow Occurs	Month	Number of Stations	Percent of Total (%)
Wet season	May	8	12.31%
	June	0	0.00%
	July	0	0.00%
	August	1	1.54%
	September	1	1.54%
	October	2	3.08%
Dry season	November	1	1.54%
	December	0	0.00%
	January	13	20.00%
	February	17	26.15%
	March	14	21.54%
	April	8	12.31%

3.4. Trend Analysis

In this study, the Mann–Kendall test was used to analyze the trends of indicators including the IR, RBF, and SD6. In this study, the *p*-value ≤ 0.05 was considered to indicate a significant trend, and, when $Z \geq 1.960$, it was regarded as an increasing trend; when $Z \leq -1.960$, it was regarded as a decreasing trend. The results of the trends of the three indicators for Taiwan are shown in Figure 4 and Table 2.

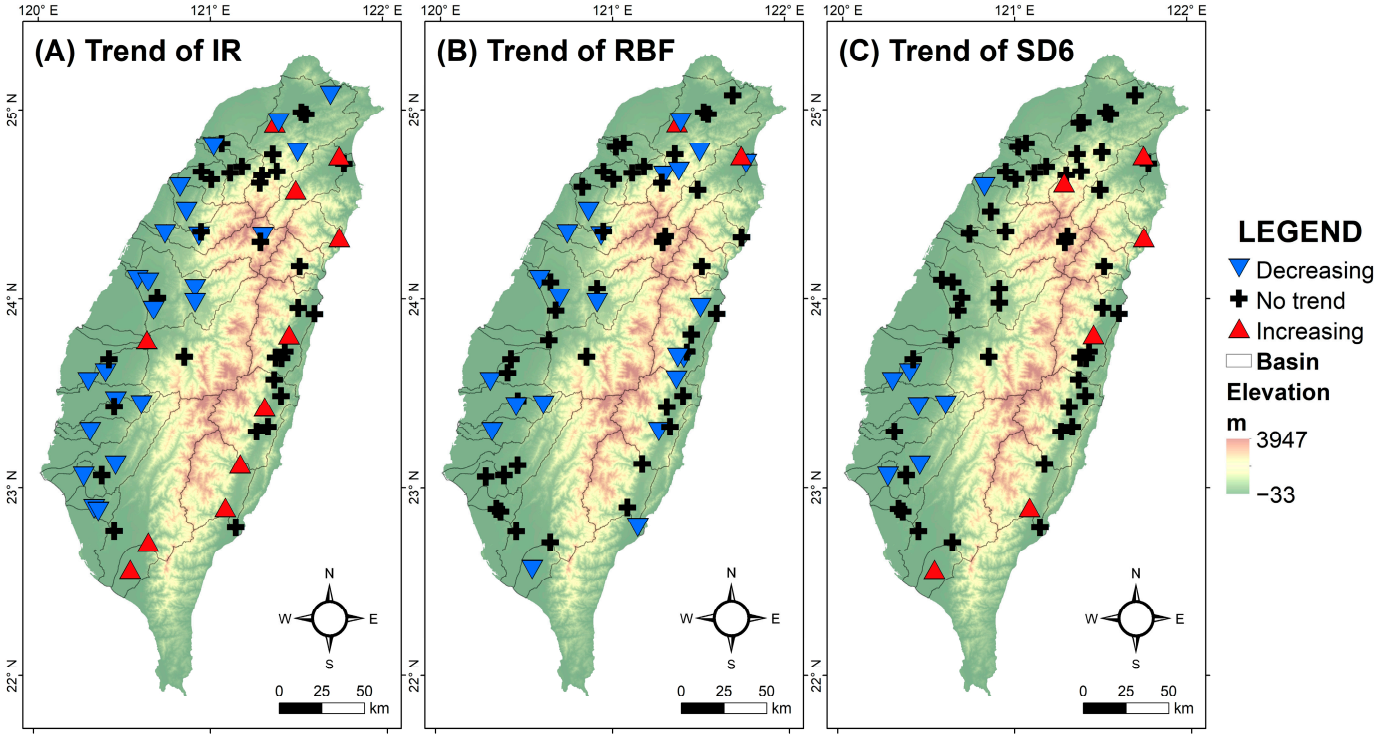

Figure 4. Trend analysis: (**A**) IR; (**B**) RBF; and (**C**) SD6; Significant increasing (red triangle) or decreasing (blue triangle) trends at the 0.05 significance level.

Table 2. Number and percentage of stations for each of the three indices at different levels of significance.

Trend Direction	Significance Level	IR		RBF		SD6	
		Number of Stations	Percent of Total	Number of Stations	Percent of Total	Number of Stations	Percent of Total
Increasing	p-value $\leq$ 0.05 *	11	16.9%	2	3.1%	6	9.2%
No trend	p-value > 0.05	31	47.7%	41	63.1%	50	76.9%
Decreasing	p-value $\leq$ 0.05 *	23	35.4%	22	33.8%	9	13.8%

Note: * The trend is significant.

Figure 4A shows the trend of the IR over time, with 11 stations showing an increasing trend, accounting for 16.9% of all stations, and were concentrated in the east of the Central Mountains. Twenty-three stations showed a decreasing trend, accounting for 35.4% of all stations, and were concentrated in the west of the Central Mountains. Thirty-one stations showed a nonsignificant trend, accounting for 47.7% of all stations. This indicates that the proportion of low-flow days at stations east of the Central Mountains is increasing and that Eastern Taiwan is becoming drier. On the contrary, the IR trend is decreasing of stations in Western Taiwan. Like the results of Sen's slope, as shown in Figure 5A and Table 3, 58.5% of the stations have a β value < 0, mostly distributed in the western half of Taiwan. Figure 4B shows the trend of the RBF index over time, with 2 stations showing an increasing trend, accounting for 3.1% of all stations, 22 stations showing a decreasing trend, accounting for 33.8% of all stations, and 41 stations showing a nonsignificant trend, accounting for 63.1% of all stations. This indicates that over half of the stations have an unchanged trend in flow variability. However, Figure 5B shows that 69.2% of the stations exhibit a decreasing trend in the RBF index, while the remaining 30.8% show an increasing trend. These stations are distributed across various regions of Taiwan, without being concentrated in any specific area.

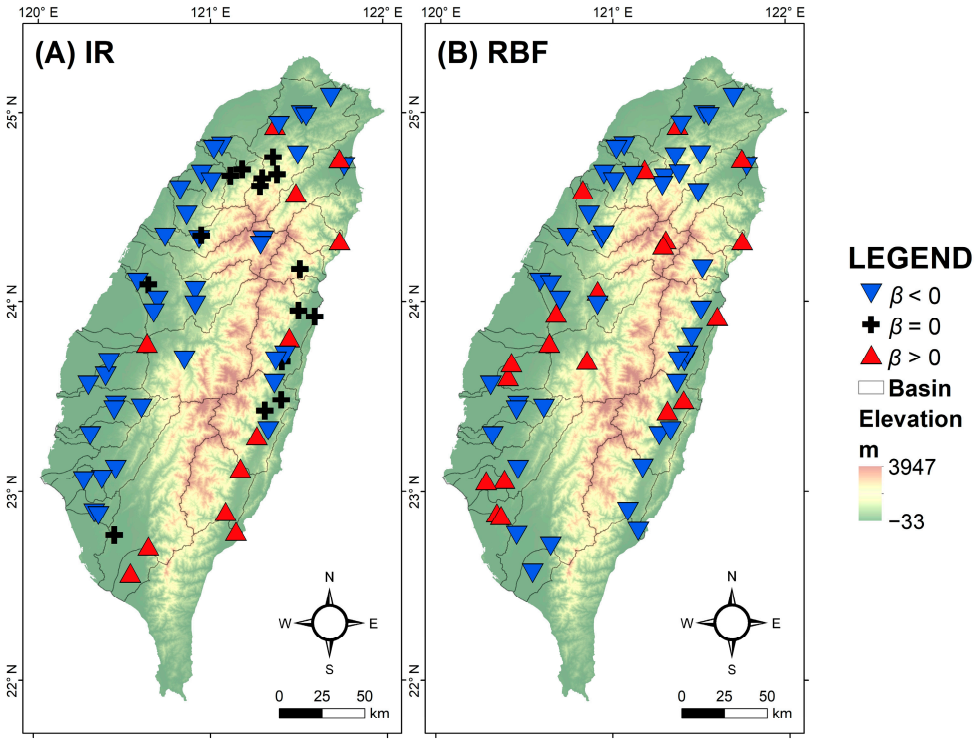

Figure 5. Sen's slope estimator of (**A**) IR; and (**B**) RBF; increasing (red triangle) or decreasing (blue triangle) trends.

Table 3. Number and percentage of stations for each of the three indices at different β values.

Trend Direction	β	IR		RBF	
		Number of Stations	Percent of Total	Number of Stations	Percent of Total
Increasing	$\beta > 0$	12	18.5%	20	30.8%
No trend	$\beta = 0$	15	23.1%	0	0%
Decreasing	$\beta < 0$	38	58.5%	45	69.2%

Figure 4C shows the trend of SD6 over time. A total of 6 stations show an increasing trend, accounting for 9.2% of all stations, 9 stations show a decreasing trend, accounting for 13.8% of all stations and distributed south of the Zhuoshui River, and 50 stations show a nonsignificant trend, accounting for 76.9% of all stations. This indicates that the seasonal occurrence of low flow in Taiwan is not affected over time. Since SD6 represents the concentration of low-flow occurrences during the six months of dry season across multiple years, it often results in zero values when calculating SD6 for individual years. Therefore, the Sen's slope for SD6 is not analyzed here.

4. Discussion

The results of river intermittency reveal that Taiwan's rivers, located within the monsoon region, are predominantly perennial. The threshold for defining intermittency varies by regional climatic conditions, and using a zero-flow threshold is not effective for analyzing the intermittency of Taiwanese rivers. Therefore, this study adopts the common low-flow threshold, q7, for evaluating intermittency. According to Aridity Index (AI) classification, Taiwan climate is categorized as humid climatic zone. Sauquet et al. [13] reported that the percentage of perennial rivers in humid regions globally is 74%, which is similar to the results of this study. This indicates that intermittency is influenced by the local climate, making the Aridity Index an important predictor of intermittency [10,13]. The method of adjusting the intermittency threshold departs from the traditional zero-flow standard. It has not only been adopted in previous studies [9,10] but also broadens its applicability

to humid regions, such as global monsoon areas, rather than remaining confined to its traditional focus on continental and Mediterranean climate zones.

The larger streamflow variation corresponding to a higher RBF index are mainly located in southwestern Taiwan. Additionally, the RBF index increases as elevation decreases from mountains (0.29) to plains (0.78). Gannon et al. [33] demonstrated that flow variability is influenced by regional or smaller scale features including climate, human activities, and subsurface structures, highlighting the diversity of factors affecting the streamflow fluctuation. However, as the specific quantification of these influencing factors is beyond the scope of this study, we rely on known data and the literature to infer possible causes. The spatial distribution and elevation patterns of the RBF index are similar to those observed for groundwater discharge into rivers in previous research [34]. Therefore, this study suggests that flow variability is closely related to groundwater discharge. Rivers with higher groundwater contributions can effectively buffer flow variability, while those with lower contributions are more likely to be dominated by flashy direct runoff. Moreover, flow variability is also affected by rainfall patterns and elevation; for instance, heavy rainfall caused by typhoons often leads to greater flow variability.

The results of low-flow seasonality show that the low-flow events at most stations in Taiwan regularly occur from November to April of the following year. Moreover, the stations west of the Central Mountain Range exhibit relatively high SD6 due to the significant socio-economic impact of spring droughts and the stronger correlation between meteorological drought and hydrological drought compared to that with agricultural drought [35]. Additionally, low-flow events include geographical features like average permeability, area, and slope [11,36]. This study suggests that the timing of low-flow events is closely related to Taiwan's rainfall distribution patterns. In northeastern Taiwan, the combined effects of the northeast monsoon and topography result in smaller SD values, indicating less pronounced seasonality. In contrast, other regions primarily receive annual rainfall from typhoons or the plum rain season, leading to SD values closer to 1 and more evident seasonality.

This study employs the Mann–Kendall Test and Sen's slope for trend analysis, both of which are commonly used non-parametric methods. The Mann–Kendall test identifies trends and their significance in time series data, while Sen's slope provides a more robust estimation of trends, particularly in the presence of outliers. However, both methods overlook the influence of auto-correlated data, failing to capture patterns of fluctuation or complex non-linear trends. This limitation reduces their sensitivity to non-linear trends, such as oscillations, phase changes, or intricate non-linear behaviors, which constrains the findings of this study. Therefore, it is recommended that future research considers using the seasonal or pre-whitening Mann–Kendall test [37,38] to account for data with seasonality or autocorrelation influence.

The trend analysis results indicate an increasing IR trend in the eastern region of Taiwan. Belemtougri et al. [11] suggested that an increase in intermittency, based on the intermittency cycle, indicates a decline in groundwater levels and reduced runoff. In each cycle of intermittency, the groundwater table drops to a level lower than in the previous cycle, gradually reducing streamflow in the river channel. This trend poses a serious risk of heading toward a future with no water if no appropriate measures are taken to address droughts of a given duration and severity.

5. Conclusions

In this study, the intermittency, variability, and seasonality of flow and trend analyses were used to understand the flow characteristics of the rivers in Taiwan. The results show that 70% of the 65 flow stations in Taiwan have an annual average IR value less than 0.1,

indicating that most rivers in Taiwan are perennial. The RBF index results show that all stations have an RBF of less than 1, which means that the flow variability is low, with the relatively higher RBF values found in the southwestern region of Taiwan. In addition, 25 stations had SD6 = 1, and the average was 0.76, meaning that the low-flow months in all rivers in Taiwan are mainly concentrated in the dry season. Direction statistics of the low-flow dates reveal that most low-flow events occur from January to March, indicating that low-flow periods typically span from winter to spring. The trend analysis shows that the intermittency ratio, flow variability and the low-flow season have nonsignificant trends at most stations. In conclusion, most rivers in Taiwan are perennial and stable, with low flows typically occurring during the dry season. The timing of low flows remains nearly the same. The results provide a reference for river and water resource management.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w17020271/s1, Table S1: Gauging stations and streamflow record years.

Author Contributions: Conceptualization, X.F., H.-Y.C. and H.-F.Y.; methodology, X.F. and H.-F.Y.; formal analysis, X.F.; data curation, X.F. and H.-Y.C.; writing—original draft preparation, X.F.; writing—review and editing, X.F. and H.-Y.C.; supervision, H.-F.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: River flow gauge stations data and daily streamflow data used in this study are accessible online at https://www.wra.gov.tw/cl.aspx?n=39575 (accessed on 1 November 2024). Digital terrain model (DTM) data used in this study are accessible online at https://data.gov.tw/ (accessed on 23 August 2023).

Conflicts of Interest: The authors declare no conflicts of interest.

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