

ANALYSIS OF TRENDS AND FREQUENCY VARIABILITY IN WATER LEVELS IN THE VIETNAMESE MEKONG DELTA USING F-IPTA

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Abstract - Human activities and climate change have altered the hydrological regime of the Vietnamese Mekong Delta (VMD), but changes in water level trends and frequency variability have not yet been fully assessed. This study uses the Frequency-based Improved Polygonal Trend Analysis (F-IPTA) method to analyze monthly water level variations at the Tan Chau and Chau Doc stations from 1979 to 2023. The results show a decline in water levels during the flood season, from July to October, for high, low, and mean water levels. Low and very low water levels have become more frequent, while high and very high levels have decreased. Transition indicators further reveal shifts in the hydrological season and water levels distribution between the two periods. These findings provide quantitative evidence of changes in the VMD hydrological regime and can support more effective water resource management.

Key words - F-IPTA; seasonal transition; hydrological alteration; anthropogenic impacts

1. Introduction

The Vietnamese Mekong Delta (VMD) is one of the largest and most fertile deltas in the world, formed by thousands of years of sediment deposition from the Mekong River [1]. It is a major agricultural region of Vietnam and contributes substantially to national food security and economic development, particularly through rice and aquaculture [2, 3]. However climate change, sea level rise, sand mining, and upstream hydropower development are increasingly affecting the delta, leading to changes in its hydrological regime and morphology [4–6].

Upstream flow regulation has also changed the seasonal distribution of Mekong River discharge. Flood season discharge has generally declined, while dry season discharge has increased following reservoir development. At Kratie station, Dang et al. reported a 12–160% increase in dry season discharge, compared with the period before 1992 [10]. Tonle Sap Lake has traditionally regulated seasonal flows between the upper and lower Mekong River [8, 11]. However, the rapid expansion of upstream hydropower dams since the 1990s has altered this natural regulation, affecting the timing and magnitude of downstream flows [12, 13]. These changes are reflected not only in mean water levels and discharge but also in their frequency and seasonal distribution. Non-parametric tests are commonly used to

analyze trends in hydro-meteorological time series, such as the Mann–Kendall (MK) test [14, 15], Sen's slope estimator [16], and Pettitt's test [17]. Many researchers have used the MK test to assess trends in hydrological, meteorological, and water quality time series [18–21]. However, they mainly describe overall monotonic trends and provide limited information on changes in the frequency of different water level classes or shifts in seasonal patterns.

Frequency based approaches have recently been combined with trend analysis to overcome these limitations. Abu Ara et al. combined frequency analysis with the ITA method [22] and found decreases in high and very high rainfall frequencies and an increase in very high temperature frequency. Similarly, Amarchi et al. reported significant changes in the frequency of standardized precipitation and drought indices in northeastern Algeria [23].

For the VMD, several recent studies have examined changes in water level variability at major hydrological stations such as Tan Chau and Chau Doc. Minh et al. reported a stronger decreasing trend in water levels at Tan Chau than at Chau Doc during 2000–2023 [24]. Huy et al. also indicated that the water level regime tends to shift from the flood season to the dry season under the influence of upstream regulation [25]. However, these studies mainly examined overall temporal trends and provided limited information on changes in the frequency distribution of different water level classes and seasonal shifts.

Recently, Alashan and Şen proposed the Frequency-based Innovative Polygon Trend Analysis (F-IPTA) method [27]. Compared with the IPTA method, which is based only on polygonal scatter plots, F-IPTA additionally integrates frequency analysis, thereby enabling clearer identification of changes in the distributional structure of data series between periods.

Therefore, this study applies the F-IPTA method to analyze monthly water level data series at the Tan Chau and Chau Doc station to assess changes in water level and identify trends in seasonal shifts of the hydrological regime under the effects of hydrological changes in the Mekong River basin.

2. Data and research methods

2.1. Study area

With a length of 4,763 km, the Mekong River is the longest river in Southeast Asia, with an estimated total annual water discharge of approximately 476 billion m³ flowing into the sea [26]. Originating on the Tibetan Plateau, it flows through China, Myanmar, Thailand, Laos, Cambodia, and Vietnam, before discharging into the East Sea of Vietnam through two main branches: the Mekong River, known in Vietnam as the Tien River, and the Bassac River, known in Vietnam as the Hau River. This study focuses on annually observed data at the Tan Chau and Chau Doc stations in An Giang Province (Figure 1). These are key hydrological stations that monitor the volume of water flowing into the downstream Mekong River.

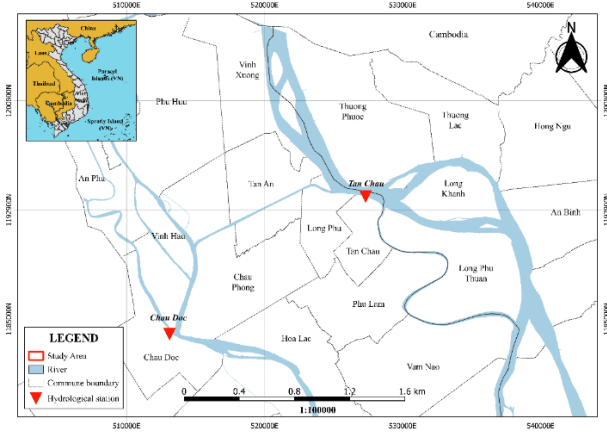


Figure 1. Study area

To assess seasonal hydrological variability, hourly water level data were collected from the Southern Regional Hydro-Meteorological Center at the Tan Chau and Chau Doc stations for the period from 1979 to 2023, as presented in Table 1.

Table 1. Data collected in the study area

Station	Variable	Period	Min	Mean	Max	Std. Dev.	Skewness
Tan Chau	Water Level	1979-2023	-0.68	1.66	5.06	1.23	0.68
Chau Doc	(m)		-0.69	1.47	4.90	1.08	0.73

2.2. Research methods

Recently, Alashan and Şen proposed the Frequency-based Innovative Polygon Trend Analysis (F-IPTA) method, which allows the simultaneous assessment of variation trends and the frequency of occurrence of seasonal hydrological values [27]. Compared with the traditional IPTA method, which is based only on polygonal scatter plots, F-IPTA additionally integrates frequency analysis, thereby enabling clearer identification of changes in the distributional structure of data series between periods.

The F-IPTA method is calculated through the following specific steps. The time series z is divided into two equal parts, x and y , to determine the slope, S_{ITA} , as shown in Equation (1):

$$S_{ITA} = \frac{2(\bar{y} - \bar{x})}{n} \quad (1)$$

where $\bar{x}$ and $\bar{y}$ are the mean values of the first and second halves of a time series with length n , respectively.

To incorporate seasonal variability, Innovative Polygon Trend Analysis (IPTA) extends ITA by dividing the two series, x and y , into a monthly matrix, as shown in Equation (2) [28]:

$$\begin{bmatrix} z_{1,1} & z_{1,2} & \dots & z_{1,11} & z_{1,12} \\ z_{2,1} & z_{2,2} & \dots & z_{2,11} & z_{2,12} \\ \vdots & \vdots & & \vdots & \vdots \\ z_{i,1} & z_{i,2} & \dots & z_{i,11} & z_{i,12} \\ \vdots & \vdots & & \vdots & \vdots \\ z_{n-1,1} & z_{n-1,2} & \dots & z_{n-1,11} & z_{n-1,12} \\ z_{n,1} & z_{n,2} & \dots & z_{n,11} & z_{n,12} \end{bmatrix} \quad \begin{matrix} \uparrow \text{First} \\ \downarrow \text{Second} \end{matrix} \quad (2)$$

Here, each row represents $z_{i,j}$, where $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, 12$, from 1 to n for two sub-series with equal lengths of monthly values. In the scatter plot, the mean values of the first half are plotted on the horizontal axis, while those of the second half are plotted on the vertical axis. This plot generates 12 scattered points, each corresponding to one month, and the points located above or below the 1:1 line indicate increasing or decreasing trends, respectively.

Furthermore, a polygon is created by connecting the points of consecutive months with straight line segments. The magnitude and slope of the seasonal transition edges are calculated based on Equations (3) and (4):

$$\text{Seasonal transition magnitude} = \sqrt{(y_{j+1} - y_j)^2 + (x_{j+1} - x_j)^2} \quad (3)$$

$$\text{Seasonal transition slope} = \frac{y_{j+1} - y_j}{x_{j+1} - x_j} \quad (4)$$

$$1 \leq j \leq 12$$

In the F-IPTA method, the number of bins for the monthly scale is set to five; however, this number may vary for weekly, daily, or other temporal scales. For the five-bin frequency diagram, these bins are classified as very low (VL), low (L), normal (N), high (H), and very high (VH). After the bins are determined, the frequency value is calculated as the percentage of the number of data points, n_i , in each bin relative to the total number of data points, n , as shown in Equation (5):

$$f_i = \frac{n_i}{n} \times 100 \quad (5)$$

3. Results and discussion

F-IPTA is a recently developed method proposed by Alashan S. and Şen Z. [27]. Unlike conventional IPTA, F-IPTA combines trend analysis with frequency analysis to detect changes in the occurrence of very low (VL), low (L), normal, high (H), and very high (VH) values. In this study, the method was used to examine changes in water level trends and frequency patterns at the Tan Chau and Chau Doc stations. The results show a shift in the seasonal hydrological regime, with lower water levels

during the flood season and more frequent low water conditions in the recent period.

3.1. Analysis of water-level variation trends at the Tan Chau and Chau Doc stations during 1979–2023

Figure 2 shows the variation trends in water levels at the Tan Chau and Chau Doc stations during the period 1979–2023 for maximum, mean, and minimum water levels. Overall, the results indicate that the hydrological regime changed between the two study periods.

Most flood-season months (July–October) are below the 1:1 line, indicating lower water levels during 2001–2023 than during 1979–2000. In contrast, during the dry season (January–May), mean and minimum water levels generally remain close to the 1:1 line, whereas maximum water are mostly above it (Figure 2). The decline during the flood season, combined with local increases during the dry season, indicates an ongoing seasonal shift in the hydrological regime.

The frequency analysis also shows more frequent VL and L classes, particularly for mean and minimum water levels, while H and VH classes become less common at Tan Chau. For maximum water levels, the VL and VH classes each account for about 33.3%, reflecting the strong contrast between dry and flood season conditions (Figure 2a). For mean and minimum water levels, the VL and L classes together account for more than 50% of the observations (Figure 2b, c), indicating that lower water levels occurred more frequently indicating a higher frequency of lower water levels in the recent period.

At Chau Doc, the shift toward lower water levels is more pronounced. For maximum water levels, the VL class accounts for 50.0%, compared with only 16.7% for the VH class (Figure 2d), indicating fewer high flood peaks during the recent period. For mean and minimum water levels, the

combined frequencies of the VL and L classes reach 58.4% and 66.7%, respectively (Figure 2e, f).

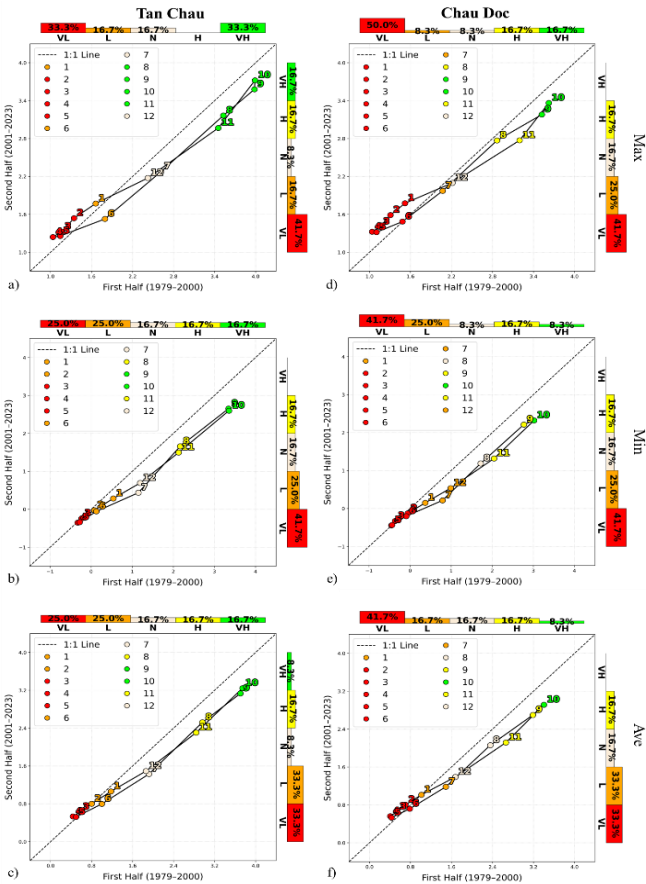


Figure 2. Comparison of variation trends and frequency distributions of monthly water-level characteristics (maximum, mean, and minimum) at the Tan Chau and Chau Doc stations between the periods 1979–2000 and 2001–2023

Table 2. Trends in monthly water level changes at Tan Chau and Chau Doc stations from 1979 to 2023

Station	Charac- teristics	Statistics (Average)	Month											
			1	2	3	4	5	6	7	8	9	10	11	12
Tan Chau	Max	First half (1979-2000)	1.66	1.34	1.16	1.03	1.14	1.80	2.62	3.53	3.98	3.99	3.45	2.42
		Second half (2001-2023)	1.77	1.54	1.33	1.24	1.26	1.53	2.28	3.16	3.58	3.72	2.97	2.18
		Trend slope (s)	0.00	0.01	0.01	0.01	0.01	-0.01	-0.02	-0.02	-0.02	-0.01	-0.02	-0.01
	Min	First half (1979-2000)	0.54	0.08	-0.23	-0.33	-0.28	0.13	1.15	2.17	3.34	3.35	2.13	1.19
		Second half (2001-2023)	0.29	-0.02	-0.24	-0.35	-0.34	-0.05	0.44	1.66	2.65	2.60	1.50	0.69
		Trend slope (s)	-0.01	0.00	0.00	0.00	0.00	-0.01	-0.03	-0.02	-0.03	-0.03	-0.03	-0.02
	Mean	First half (1979-2000)	1.18	0.80	0.57	0.44	0.50	1.00	1.92	2.96	3.70	3.74	2.84	1.86
		Second half (2001-2023)	1.06	0.80	0.63	0.53	0.52	0.80	1.43	2.52	3.13	3.24	2.30	1.49
		Trend slope (s)	-0.01	0.00	0.00	0.00	0.00	-0.01	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02
Chau Doc	Max	First half (1979-2000)	1.52	1.31	1.16	1.04	1.10	1.48	2.07	2.87	3.52	3.62	3.20	2.21
		Second half (2001-2023)	1.78	1.59	1.40	1.33	1.32	1.49	1.97	2.77	3.18	3.36	2.77	2.10
		Trend slope (s)	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	-0.02	-0.01	-0.02	-0.01
	Min	First half (1979-2000)	0.37	-0.06	-0.37	-0.45	-0.44	-0.09	0.79	1.72	2.77	3.02	2.04	0.99
		Second half (2001-2023)	0.15	-0.13	-0.33	-0.44	-0.44	-0.20	0.21	1.19	2.21	2.32	1.32	0.54
		Trend slope (s)	-0.01	0.00	0.00	0.00	0.00	0.00	-0.03	-0.02	-0.02	-0.03	-0.03	-0.02
	Mean	First half (1979-2000)	1.01	0.70	0.53	0.41	0.43	0.79	1.49	2.36	3.19	3.40	2.66	1.68
		Second half (2001-2023)	1.01	0.80	0.66	0.56	0.53	0.72	1.18	2.06	2.70	2.91	2.12	1.39
		Trend slope (s)	0.00	0.00	0.01	0.01	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01

Table 2 shows clear changes in water levels at Tan Chau between 1979–2000 and 2001–2023. Maximum water levels declined in all flood season months (July–November), with the largest decreases occurring from July to September at about -0.02 m/year. In contrast, several dry season months, especially January – May, show slight increases. Similar trends are observed for mean and minimum water levels, with flood season declines of -0.02 to -0.03 m/year and relatively stable or slightly increasing levels during the early months of the year. The decline in minimum water levels from July to November further indicates a substantial reduction in flood season water levels in the recent period.

3.2. Comparison of hydrological seasonal shifts between the Tien and Hau rivers

Table 3 presents the inter-monthly transition indices at the Tan Chau and Chau Doc stations. The transition length varies by season, indicating changes in water level between consecutive months. At Tan Chau, the largest transition lengths occur during July – August and November – December, reaching about 1.3 for maximum water levels. For minimum water levels, the highest values occur during July–August and October–November, reaching 1.6. This indicates strong changes in water levels during the flood season transition period. In contrast, transition lengths during March – April and April–May are only 0.0–0.2, indicating relatively stable water levels during the dry season.

The transition values at Tan Chau are generally higher than those at Chau Doc, particularly for the maximum and minimum water level. During July–August, values at Tan Chau range from 1.3 to 1.6, compared with 1.1 – 1.3 at Chau Doc. Most transition slopes at both stations range from 0.1 to 1.4, except during September–October. At Tan Chau, the slope reaches 19.5 for maximum water levels and -6.0 for minimum water levels, compared with 1.8 and 0.4 at Chau Doc. For mean water levels, the September–October transition slope is 2.7 at Tan Chau

and 1.0 at Chau Doc. These results indicate a sharper change in water levels at Tan Chau during the late flood season, particularly from September to October, than at Chau Doc. This contrast suggests a stronger seasonal transition in the Tien River than in the Hau River. The relationship between influencing factors and the decline in flood flow is reflected in the analytical results in Section 3.1. At Tan Chau, water levels decrease during most flood season months, particularly from August to October, while the frequencies of H and VH classes decline during 2001–2023 relative to 1979–2000. In contrast, VL and L classes become more frequent, indicating changes in the hydrological regime in the study area. These results are consistent with previous studies by Xue et al. [12], Binh et al. [2, 8], Pawar et al. [30], Minh et al. [24], and Huy et al. [25], which showed that the operation of dam systems in the Mekong Basin is one of the causes of significant changes in the magnitude and timing of flood season flow. Riverbed sand mining may also lower water levels by altering channel morphology and the relationship between discharge and water level [6]. Climate variability and other human activities may further contribute to these changes. The decreases in maximum and mean water levels during August–October, together with the lower frequency of the VH class, are consistent with previous studies reporting changes in flood characteristics in the VMD [25, 29–31]. In contrast, minimum water levels increase slightly in some early dry season months. This pattern may partly reflect upstream flow regulation and reservoir releases during the dry season [25, 29, 31].

The changes in transition lengths and slopes also indicate shifts in the timing and rate of seasonal water level changes. Overall, the results suggest that human regulation has increasingly affected the seasonal hydrological regime at Tan Chau, with lower flood season water levels and relatively stable or slightly higher levels during parts of the dry season [30, 31].

Table 3. Statistics of monthly water level transition characteristics at Tan Chau and Chau Doc stations

Station	Characteristics	Statistics	Transitions											
			1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-1
Tan Chau	Max	Transition lengths	0.4	0.3	0.2	0.1	0.7	1.1	1.3	0.6	0.1	0.9	1.3	0.9
		Transition slopes	0.7	1.2	0.7	0.1	0.4	0.9	1.0	0.9	19.5	1.4	0.8	0.5
	Min	Transition lengths	0.6	0.4	0.1	0.0	0.5	1.1	1.6	1.5	0.1	1.6	1.2	0.8
		Transition slopes	0.7	0.7	1.2	0.2	0.7	0.5	1.2	0.8	-6.0	0.9	0.9	0.6
	Ave	Transition lengths	0.5	0.3	0.2	0.1	0.6	1.1	1.5	1.0	0.1	1.3	1.3	0.8
		Transition slopes	0.7	0.8	0.7	-0.2	0.5	0.7	1.0	0.8	2.7	1.0	0.8	0.6
Chau Doc	Max	Transition lengths	0.3	0.2	0.1	0.1	0.4	0.8	1.1	0.8	0.2	0.7	1.2	0.8
		Transition slopes	0.9	1.2	0.7	-0.1	0.4	0.8	1.0	0.6	1.8	1.4	0.7	0.5
	Min	Transition lengths	0.5	0.4	0.1	0.0	0.4	1.0	1.3	1.5	0.3	1.4	1.3	0.7
		Transition slopes	0.7	0.7	1.3	0.5	0.7	0.5	1.1	1.0	0.4	1.0	0.7	0.6
	Ave	Transition lengths	0.4	0.2	0.2	0.0	0.4	0.8	1.2	1.0	0.3	1.1	1.2	0.8
		Transition slopes	0.7	0.9	0.7	-1.3	0.5	0.7	1.0	0.8	1.0	1.1	0.7	0.6

4. Conclusion

This study applied the F-IPTA method to assess changes in water levels at the Tan Chau and Chau Doc hydrological stations during 1979–2023. The results show clear changes in the hydrological regime between 1979–2000 and 2001–2023.

(1) The results of the F-IPTA diagrams and trend indices show that, during the flood season (July–November), maximum, mean, and minimum water levels generally decreased at both stations, with trend slopes ranging from -0.01 to -0.03 m/year. The largest decline occurred in the minimum water level during September–November, with a slope of $s = -0.03$ m/year. In contrast, water levels during the dry season (January–May) changed little, with slopes close to 0.00 m/year or slight increases ($s = +0.01$), particularly for maximum water levels.

(2) The F-IPTA frequency analysis indicates a shift in the distribution of water levels between the two periods. At Chau Doc, the VL class accounted for 50.0% of the maximum water level observations, while the VH class decreased to 16.7%. The combined frequencies of the VL and L classes accounted for 58.4% of mean and 66.7% of minimum water levels. Similar shifts were found at Tan Chau, where the combined VL and L classes accounted for more than 50% of mean and minimum water levels. These changes indicate fewer high water events and lower flood peaks, providing quantitative evidence of a weakening flood regime in the upstream VMD.

The increase in the proportion of low water level classes, together with the contraction of high water level classes, indicates fewer high-water events and lower flood peaks, providing quantitative evidence of a weakening flood regime in the upstream VMD.

(3) The transition length and transition slope indices further show clear changes in the characteristics of the hydrological season. Transition length tends to increase during June–August and November–December, indicating greater water level variability during seasonal transitions. Tan Chau showed stronger transition than Chau Doc, particularly during September–October, when the transition slope reached 19.5 for maximum water levels and -6.0 for minimum water levels. This suggests more abrupt changes in water levels at Tan Chau, especially for extreme conditions.

(4) The synthesis of the above three groups of results, including the declining trend in flood season water levels, the frequency shift from high to low frequency classes, and changes in seasonal transition characteristics, indicates a clear change in the hydrological during 2001–2023 relative to 1979–2000. Unlike conventional IPTA, which mainly identifies trends F-IPTA incorporates frequency information and quantifies changes across water level classes. This approach can support hydrological monitoring and water resource management in the VMD under increasing upstream pressures.

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