BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

ARTICLE

Hydrological Regime Variability between the Tien and Hau Rivers under the Impact of Anthropogenic Activities and Climate Change

Nguyen Dam Quoc Huy [1,2,3] ***, Tran Thi Kim*** [4] ***, Dang Truong An*** [1,2,*]

[1] *Department of Oceanology, Meteorology and Hydrology, Faculty of Physics-Engineering Physics, University of Science, Ho Chi Minh City 700000, Vietnam*

[2] *Viet Nam National University-Ho Chi Minh, Ho Chi Minh City 700000, Vietnam*

[3] *Institute of Coastal and Offshore Engineering, HCM City 700000, Vietnam*

[4] *Faculty of Environment, Ho Chi Minh City University of Natural Resources and Environment, Ho Chi Minh City 700000, Vietnam*

ABSTRACT

The distribution of flow discharge between the Tien and Hau Rivers in the Vietnamese Mekong Delta (VMD) plays an important role in Vietnam's agricultural and aquaculture production activities. However, recent variations in water levels and flow patterns, driven by both human activities and climate change (CC), have posed significant challenges for water resource management. This study evaluates the impacts of unsustainable exploitation and CC on the hydrological regime of the Tien and Hau Rivers using non-parametric statistical methods. Long-term water level data (1978–2023) from Tan Chau, Chau Doc, and Vam Nao observation stations were analyzed using the Mann-Kendall test (MK), Sen's Slope (SS) estimator, and Pettitt's test to detect trends, quantify change magnitudes, and identify abrupt shifts. The results indicate a significant decline in flood-season water levels, with annual decrease rates ranging from 41.5 to 72.9 mm in September and November. Conversely, a slight increasing trend in water levels was observed in the dry season (DS) during the studied time. Additionally, findings reveal that the upstream Tien River exerts greater control over the hydrological regime in the Vam Nao River. These insights contribute to disaster risk assessment, sustainable water resource planning, and ecological

*CORRESPONDING AUTHOR:

Dang Truong An, Department of Oceanology, Meteorology and Hydrology, Faculty of Physics-Engineering Physics, University of Science, Ho Chi Minh City 700000, Vietnam; Viet Nam National University-Ho Chi Minh, Ho Chi Minh City 700000, Vietnam; Email: dtan@hcmus.edu.vn

ARTICLE INFO

Received: 10 February 2025 | Revised: 24 February 2025 | Accepted: 26 February 2025 | Published Online: 23 April 2025

DOI: https://doi.org/10.30564/jees.v7i5.8707

CITATION

Huy, N.D.Q., Kim, T.T., Truong An, D., 2025. Hydrological Regime Variability between the Tien and Hau Rivers under the Impact of Anthropogenic Activities and Climate Change. Journal of Environmental & Earth Sciences. 7(5): 96–107. DOI: https://doi.org/10.30564/jees.v7i5.8707

risk evaluation. Furthermore, the results contribute to providing a foundation for applying hydrological and hydraulic models to forecast hydrodynamics, thereby supporting effective water management strategies and mitigating flood and dry risks in the VMD.

Keywords: Vietnamese Mekong Delta; Water Flow Distribution; Non-Parametric Tests; Upstream; Vam Nao

1. Introduction

The VMD is one of the world's largest and most dynamic deltas [1, 2], supporting approximately 17 million people and contributing around 18% of Vietnam's GDP through rice and fisheries production [3, 4]. The delta's economic development is largely driven by natural floods that transport a massive amount of nutrient-rich suspended sediment along the Mekong's main channel, and an abundant fishery supply from upstream [5, 6]. However, the sustainable development of the VMD is increasingly threatened by various factors, both inland and coastal, including climate change, extreme climatic events (ECEs), and the construction of major upstream dams that affect freshwater flow downstream [7, 8]. These factors directly impact the regime of water flowing into the VMD, leading to significant changes in river morphology, which have become major challenges for rivers worldwide [9, 10]. The construction of dams, CC, sea level rise (SLR), land use changes, and the development of dyke systems have altered the natural hydro-geomorphological characteristics of the VMD [11–13]. In July 2019, the VMD detected its lowest water level in 100 years [9, 11, 14], and in 2020, the VMD experienced the most severe saltwater intrusion disaster ever recorded [15, 16]. Numerous studies have demonstrated that dams have strongly changed flow patterns in the VMD by reducing water flow in the flood season (FS) while increasing it in the dry season (DS) [14, 17, 18]. For instance, Minh et al. [15] conducted a comprehensive analysis of water level trends at the upper stations of the VMD from 2000 to 2023. Their results showed a more significant decline at Tan Chau compared to Chau Doc, with an annual decrease ranging from 71.4 to 93.2 mm. However, the impact of dams on the Mekong River's flow patterns is still a topic of debate, with some studies arguing that droughts are primarily driven by climatic factors [14, 19, 20]. Additionally, rampant sand mining has exacerbated riverbed erosion, significantly affecting the flow dynamics [21–23]. The wetland ecosystems of the VMD are particularly vulnerable to the impacts of CC and the upstream hydropower dams (UHDs) projects [24–26]. Ecological imbalance, reduced floodwater retention capacity, and lower groundwater levels cause wetland areas to dry out more quickly, with severe consequences for wetland biodiversity [26–28].

The Vam Nao River is approximately 6.5 km long, 700 m wide, and has a depth exceeding 17 m [29]. It is the only river segment that directly connects the Tien River and Hau River [30, 31]. The Vam Nao River serves as a natural link between the two main branches of the Tien River and Hau River [32, 33]. The tide on the Hau River propagates to the Tien River during the dry season through reverse flow [7, 31].

According to existing studies, many researchers have conducted studies on water allocation between the Tien and Hau Rivers, riverbed erosion and deposition, scouring pit migration, and bank erosion along the Vam Nao River [6, 31, 34]. However, a comprehensive study covering stations across the VMD has not yet been conducted and current studies have yet to fully assess the change in water flow distribution between the Tien and Hau Rivers, which significantly impacts the downstream wetland ecosystems. This study aims to address these knowledge gaps by examining the hydrological regime variations between the Tien and Hau Rivers under the impact of unsustainable exploitation and climate change.

2. Materials and Methods

2.1. Study Area and Data

The Mekong River is the longest river in Southeast Asia, stretching 4,763 km, with an average annual flow rate of approximately 15,000 $m^3 s^{-1}$ [35]. The river originates from the Tibetan Plateau, flowing through six countries and empties into the East Sea of Vietnam through two main branches the Tien River and the Bassac River [35, 36]. The VMD has a relatively low elevation, ranging from 0.5 to 4.5 m.a.s.l [20, 29]. The region has a dense network of channels connected to the East Sea of Vietnam and the Gulf of Thailand [20, 35]. The Vam Nao River is where water circulates between the Tien and Hau rivers (**Figure 1**), helping to balance the flow to the East Sea [8, 20]. Typically, high flow occurs during the FS, while low flow happens in the DS, with the transitional months being June and December (**Figure 2**). In addition, the hydrological regime of the study area is also influenced by tides from the East Sea and the West Sea [20, 24]. Recently, unsustainable exploitation and climate change have altered the flow regime during the flood and dry seasons [20, 24]. The flood pulse submerges the upper part of the delta during the FS, while in the DS, saltwater intrusion increases significantly [9, 16, 17]. The construction of upstream projects may contribute to enhancing flow regime changes in this area [18, 23, 35]. In addition, CC is the main cause of rainfall changes in the VMD, leading to changes in the regional hydrological regime [24, 35].

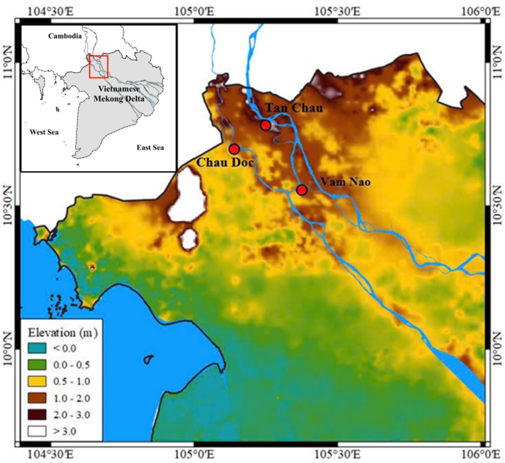

Figure 1. The study area in the Vietnamese Mekong Delta.

In this study, water level data were collected at three stations Tan Chau, Chau Doc, and Vam Nao during the period of 1978–2023 (Vam Nao station from 1984 to 2023). As for the flow discharge, data at Tan Chau and Chau Doc stations were collected from 1978 to 2023.

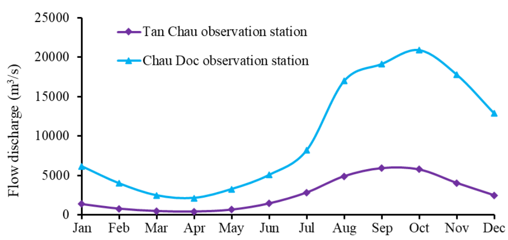

Figure 2. Distribution of flow discharge across observation stations.

2.2. Methods

2.2.1. Pettitt's Test

Quality assessment of data series is the process of checking and evaluating the quality of collected data over a time series or from different sources [37, 38]. The goal is to ensure that the data used is reliable, complete, consistent, and accurate, so it can serve for research, analysis, and decision-making [39, 40]. In the study, the Pettitt test was used to assess the homogeneity of flow features at observation hydrological stations [37, 39]. The Pettitt test is commonly used in several hydrological and climate studies to detect sudden changes in the input data series [37, 39]. The expression for the Pettitt method is given in Equation (1).

$$P_k = 2 * \sum_{i=1}^{k} r_i - k(N-1); k = 1, 2, ..., N \quad (1)$$

Where: r_i represents the increasing rank of the data series $r_1, r_2, r_3, ..., r_N$

The test is useful for detecting the changes in the data series without assuming a specific distribution, such as normal distribution. In the case where the data is interrupted at year y when the value P_k is maximized at P_y:

$$P_y = \max |P_k| \text{ with } (1 \leq y < N) \quad (2)$$

The value of P_y is simulated by Pettitt (1979) at α = 0.05. In the case where the data is interrupted at year y when the value P_k is maximized at P_y:

2.2.2. MK Test

The MK test is a widely used for trend analysis in time series, such as meteorology, hydrology, and environmental studies [41, 42]. The method is particularly useful when dealing with data that contains abnormal or inconsistent elements [38, 40].

The MK test is based on assessing the relationship between pairs of values in the time series to detect the existence of trends [38, 41]. In the testing process, the null hypothesis (H_0) assumes that there is no trend in the data series and that the values in the data series ($x_{i,j}$ = 1, 2, ..., n) are independent and have a uniform distribution [39, 42].

In this case, the statistical index S is defined by Equation (3):

$$S = \sum_{i}^{N-1} \sum_{j=i+1}^{N} sgn(x_j - x_i) \quad (3)$$

$$sgn(x_j - x_i)\begin{cases} +1\, if\ x_j - x_i > 0 \\ 0\, if\ x_j - x_i = 0 \\ -1\, if\ x_j - x_i < 0 \end{cases}$$

When S > 0, it implies an uptrend while S < 0, it implies a downtrend.

The variance of S is determined using Equation (4):

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\right] \tag{4}$$

Where: g is the number of groups with repeated values, t_p is the number of times the value p appears.

The standardized value Z of S follows a normal distribution, as given by Equation (5):

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & khi\ S > 0 \\ 0 & khi\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & khi\ S < 0 \end{cases} \tag{5}$$

Z follows a standard normal distribution N(0,1) and is used to test whether the series has a trend or not at a given significance level (in this study, $\propto = 0.05$).

The Kendall correlation coefficient (τ): $\tau = \frac{S}{D}$, where D is the maximum possible value of S, $-1 < \tau < 1$.

2.2.3. Sen's Slope Estimation

The Sen's slope method, proposed by Sen (1968)[42, 43], is an effective tool for analysing trends in time series[44, 45]. The method is particularly useful if the data series does not exhibit a normal distribution or contains outliers, as it is based on the median rather than the mean, thereby minimizing the impact of anomalies in the data[41, 44]. The Sen's slope estimation method is a reliable approach to estimating the slope of a linear trend in a time series[41, 42]. It is particularly useful when the data is not normally distributed or contains outliers, as it is less sensitive to the presence of these anomalies[41, 43]. The method is based on the concept of the median, which is a more robust estimator than the mean in the presence of outliers[42–44].

The slope is calculated by identifying all pairs of observed values in the series and applying the following Equation (6):

$$Q_i = \frac{x_j - x_i}{j - i} \tag{6}$$

Where: x_j, x_i are the values at times, and n is the number of data points. From the set of values Q, which are arranged in order, the median value Q_{med} is used to represent the slope of the trend. The median value is determined by the following Equation (7):

$$Q_{med} = \begin{cases} Q_{[(N+1)/2]} & if\ N\ is\ odd \\ \frac{Q_{[(N/2]} - Q_{[(N+1)/2]}}{2} & if\ N\ is\ even \end{cases} \tag{7}$$

Where: $N = \frac{n(n-1)}{2}$ is the total number of pairs of values calculated from the data series with n observations.

A trend is considered increasing if Q_{med} is positive, decreasing if the value is negative, and unchanged if the value is 0.

The confidence interval of the slope[45] is calculated using Equation (8):

$$C_\propto = Z_1 - \propto /2\sqrt{Var\,(S)} \tag{8}$$

Where: $Z_1 - \propto /2$ is the confidence interval based on the standard value. If the confidence interval of Q_{med} does not include 0, the trend is defined as statistically significant.

The Sen's slope method has been commonly used in fields such as hydrology, meteorology, and environmental studies to analyze trends in natural factors like water levels, rainfall, or temperature. With its flexibility and ability to handle non-normal data, this method has proven effective in analysing complex natural systems.

2.2.4. Innovative Trend Analysis (ITA)

ITA, introduced by Şen[44, 45], is a novel method that breaks away from traditional approaches by eliminating several key assumptions[45]. Unlike traditional methods, ITA does not assume an autonomous structure of the time series, normality of data distribution, or restrictions on data length[40, 41, 45]. By creating a scatter plot with the first half of the time series on the X-axis and the second half on the Y-axis, ITA provides a straightforward visual interpretation of trends[42, 45]. This makes it easier to identify patterns and anomalies in the data.

3. Results and Discussion

3.1. Evaluation Results of Water Level Trends

To assess the impact of unsustainable exploitation and CC on the flow regimes, we divided the water level data into two stages including pre-dam (before 1992) and post-dam (1992–2023). The Pettitt test revealed that the water levels during the period from 1978 to 1992 at the observation stations were homogeneous (**Table 1**). The chart at Tan Chau showed no sudden change points, with the water level maintaining a stable level, fluctuating slightly, and no significant increasing/decreasing trends. Similarly, the data of maximum water level (H_{max}), average water level (H_{ave}), and minimum water level (H_{min}) at Chau Doc were stable. The Pettitt test did not show any abrupt changes, confirming the homogeneity of the data series. At the Vam Nao station, the data remained stable with no major fluctuations. The results showed that there was no clear trend in the water levels during this period, as confirmed by the MK test at α = 0.05 (**Table 1**).

The results reveal that the water levels at the three stations were relatively stable before the construction of dams. The analyzed results of the Pettitt test and MK test confirmed that there was no significant trend in the water levels during this period. This suggests that the water levels were not affected by any external factors, such as human activities or climate change. At the Tan Chau station, the analyzed results of water level in the stage from 1992 to 2023 revealed a significant change in the river's water level. A change point occurred in 2011 (p = 0.05) for H_{max} and H_{ave}, while H_{min} occurred earlier in 2008 (**Table 1**), with values decreasing by 41.4 mm yr^{-1}, 22.26 mm yr^{-1}, and 8.9 mm yr^{-1}, respectively. This decrease in water levels is particularly notable in the flood months (Sep. and Nov.), where the trend shifted from increasing to decreasing, with a rate of 34.5 to 73.0 mm yr^{-1} for H_{max} and H_{ave}, while H_{min}. The results emphasized the impact of the change point in 2011 on the water levels at the Tan Chau station. The increasing trend observed in the dry season water levels (April) and the subsequent decline in water levels during the FS suggest that the river's behavior has changed significantly. This change may be contributed to the factors, including changes in precipitation patterns, human activities, or other environmental factors.

Similarly to the Tan Chau station, the Pettitt test results at the Chau Doc station showed homogeneity for the period 1978–1992 with no clear trends detected (**Table 1**). However, from 1992 to 2023, the water level fluctuations showed similar trends to those observed at Tan Chau, but the change points for the water levels differed from those at Tan Chau. The Pettitt test results indicated that H_{min} changed the earliest, followed by H_{max}, and lastly H_{ave}. This suggests that the Chau Doc station also experienced a change in water level behavior around 2011, but the magnitude and direction of the change were different from those at Tan Chau. The results recorded the key role of considering the specific characteristics of each station when analyzing water level trends. While the Tan Chau and Chau Doc stations showed similar trends, the change points and magnitudes of the changes were different. This suggests that the underlying drivers of the changes in water level behavior may be different at each station.

At Vam Nao station, the analysis results for the stage 1984–1992 showed that the data series was homogeneous, similar to the two stations above, with no trends detected at the Vam Nao station (**Table 1**). However, during the period 1992–2023, the results at the Vam Nao station showed differences compared to Tan Chau and Chau Doc stations. The Pettitt test results indicated homogeneity for H_{max} and H_{min}, but a change occurred for the H_{ave} value in 2011 (the same as the change year for Tan Chau station). This suggests that the Vam Nao station also experienced a change in water level behavior around 2011, but the magnitude and direction of the change were different from those at Tan Chau and Chau Doc stations. The results of this study highlight the importance of considering the specific characteristics of each station when analyzing water level trends. While the Vam Nao station showed differences compared to Tan Chau and Chau Doc stations, it also experienced a change in water level behavior around 2011. This suggests that the underlying drivers of the changes in water level behavior may be different at each station.

The results of trend analysis of water level characteristics at observation stations in the stage 1984–1992 are illustrated in **Figures 3–5**. For Tan Chau station (**Figure 3**), the Mann-Kendall trend analysis only identified a decreasing trend for H_{ave}, while no trend was found for H_{max} and H_{min} at Vam Nao station. A detailed monthly analysis showed that the H_{max} recorded a slight increasing trend in some months, particularly in January and April, with slopes of 14.0 mm yr^{-1} and 18.7 mm yr^{-1}, reflecting an increase in peak flow during the DS.

However, the H_{min} recorded a sharp decreasing trend, especially in September and November, with slopes of 52.3 mm yr^{-1} and 38.8 mm yr^{-1}, indicating the risk of severe water scarcity during the FS (**Figure 5**). For Chau Doc station,

Table 1. Statistical features of water levels at observation stations during the period 1978–2023.

Value	Statistical Analysis				MK Test			Pettitt's Test
	Mean	**Max**	**Min**	**SD**	**Kendall's Tau**	**P-Value**	**Sen's Slope**	**P**
Tan Chau Station								
Max	3.96	5.06	2.55	0.64	–0.28	0.005	–0.020	0.008
Ave	1.67	2.39	0.94	0.33	–0.35	0.001	–0.012	0.001
Min	–0.39	–0.18	–0.76	0.13	–0.15	0.126	–0.002	0.026
Chau Doc Station								
Max	3.55	4.9	2.35	0.62	–0.269	0.008	–0.019	0.009
Ave	1.48	2.21	0.97	0.27	–0.279	0.006	–0.008	0.005
Min	–0.51	–0.28	–0.69	0.11	0.035	0.732	0.001	0.083
Vam Nao Station								
Max	2.94	3.73	2.23	0.39	–0.035	0.762	–0.002	0.213
Ave	1.24	1.74	0.90	0.20	–0.121	0.279	–0.003	0.116
Min	–0.62	–0.41	–0.89	0.11	0.187	0.091	0.003	0.001

the MK trend analysis only identified a decreasing trend for H_{ave}, while no trend was found for H_{max} and H_{min} at Vam Nao station.

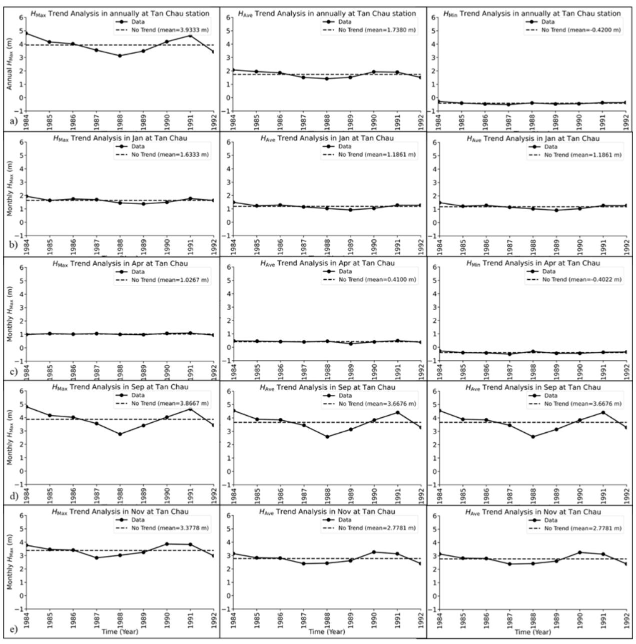

Figure 3. Change trends in annually (**a**) and monthly (**b–e**) water levels at Tan Chau station during the stage 1984–1992 based on the MK test.

A detailed monthly analysis showed that the H_{max} recorded a slight increasing trend in some months, particularly in January and April, with slopes of 14.0 mm yr^{-1} and 18.7 mm yr^{-1}, reflecting an increase in peak flow during the DS. However, the H_{min} showed a sharp decreasing trend, especially in September and November, with slopes of 52.3 mm yr^{-1} and 38.8 mm yr^{-1}, indicating the risk of severe water scarcity during the FS (**Figure 4**).

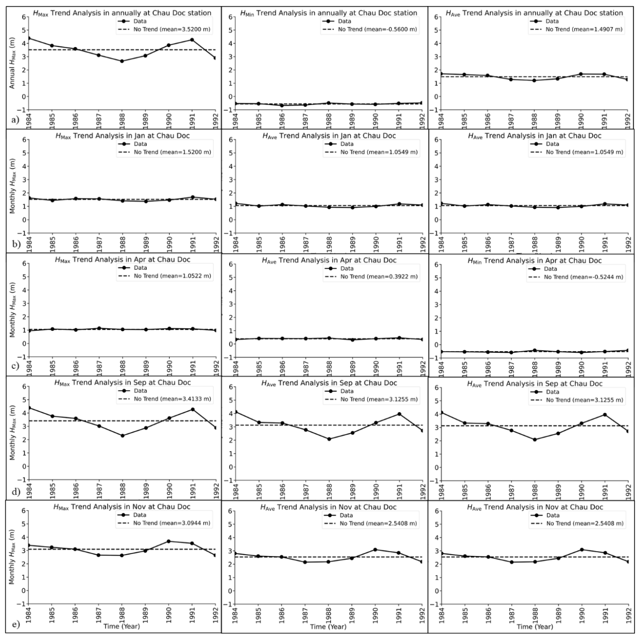

Figure 4. Change trends in annually (**a**) and monthly (**b–e**) water levels at Chau Doc station during the stage 1984–1992 based on the Mann–Kendall test.

The results of trend analysis of water level characteristics at observation stations in the stage 1992–2023 are illustrated in **Figures 6–8**. The Mann-Kendall trend analysis only identified a decreasing trend for H_{ave}, while no trend was found for H_{max} and H_{min} at Vam Nao station. A detailed monthly analysis showed that the H_{max} recorded a slight increasing trend in some months, particularly in January and

April, with slopes of 14.0 mm yr^{-1} and 18.7 mm yr^{-1}, reflecting an increase in peak flow during the DS (**Figure 8**). However, the H_{min} showed a sharp decreasing trend, especially in September and November, with slopes of 52.3 mm yr^{-1} and 38.8 mm yr^{-1}, indicating the risk of severe water scarcity during the FS.

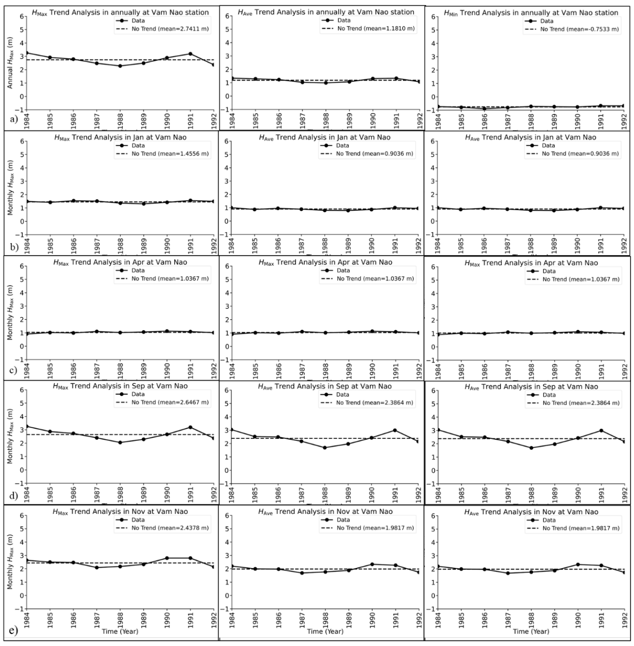

Figure 5. Change trends in annually (**a**) and monthly (**b–e**) water levels at Vam Nao station during the stage 1984–1992 based on the Mann–Kendall test.

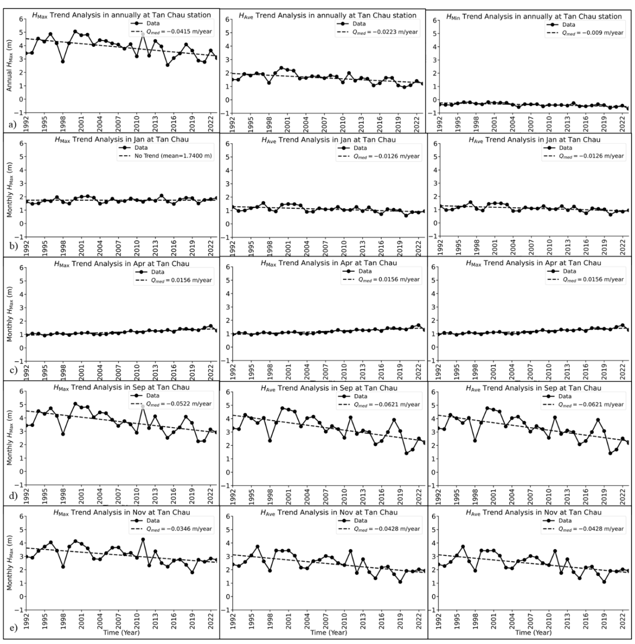

Figure 6. Change trends in annually (**a**) and monthly (**b–e**) water levels at Tan Chau station during the stage 1992–2023 based on the Mann–Kendall test.

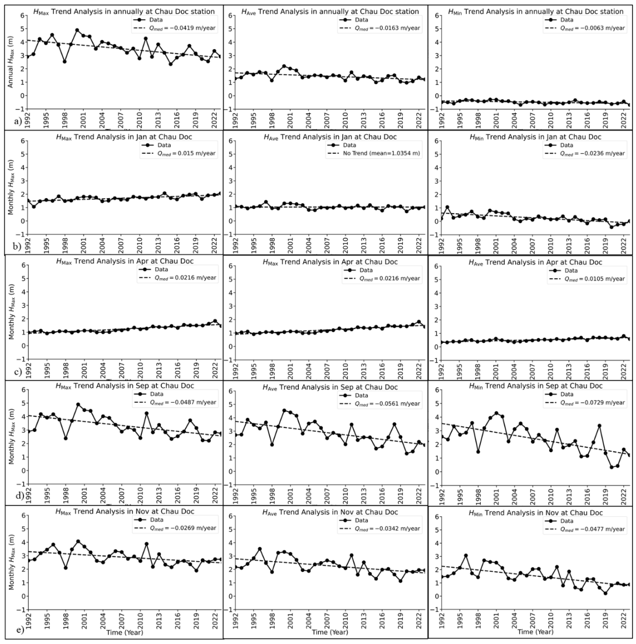

Figure 7. Change trends in annually (**a**) and monthly (**b–e**) water levels at Chau Doc station during the stage 1992–2023 based on the MK test.

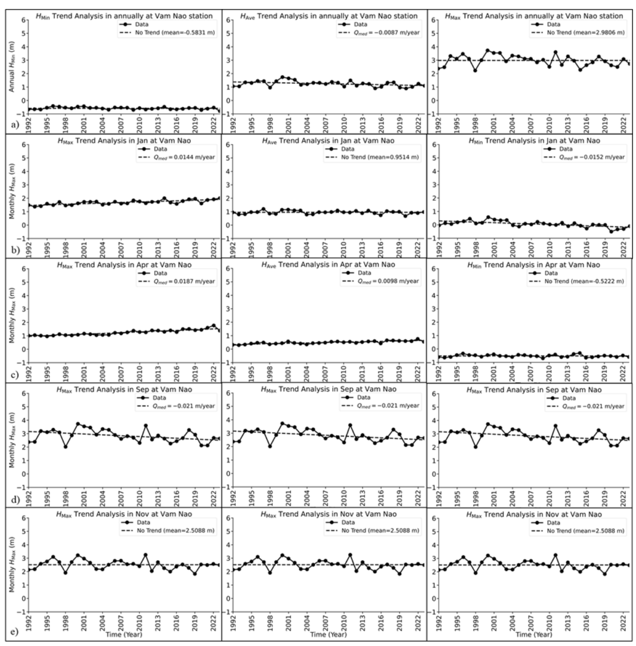

Figure 8. Change trends in annually (**a**) and monthly (**b–e**) water levels at Vam Nao station during the stage 1992–2023 based on the Mann–Kendall test.

The results of this study show significant changes in the hydrological regime between the Tien and Hau Rivers from 1992 to 2023. The data from the Tan Chau station recorded a change point in 2011 (p = 0.05) for H_{max} and H_{ave}, while H_{min} occurred earlier in 2008. This is consistent with historical flood data. In 2008, the Mekong River experienced unusually high-water levels in the upper reaches, leading to large floods in some areas.

These floods may have caused fluctuations in water levels in the downstream regions, with the Tien River being affected by larger-than-usual amounts of water flowing from upstream. Prior to 2008, several UHDs in the upper Mekong River began operations, leading to changes in the flow regime. These dams altered the water distribution mechanism, disrupting the natural flow to the downstream regions. For the 2011 event, the VMD experienced one of the largest floods in history. At Tan Chau station, large amounts of water flowing from upstream caused abnormally high peak flood levels. Additionally, floods may have altered the flow regime, leading to subsequent fluctuations in water levels.

After this period (post-2011), many UHDs in the Mekong upper catchment became operational. These dams may have dominated the water volume and adjusted the flow cycles, causing significant changes in the FS water levels at Tan Chau station. The FS water levels showed a sharp decline, from 34.5 to 73.0 mm yr^{-1} in both H_{max}, H_{min}, and H_{ave}. Meanwhile, the dry season water levels (April) showed an increasing trend of 15.5 and 5.3 mm yr^{-1} for H_{max} and H_{ave}, respectively.

Unsustainable exploitation activities have led to impacts on downstream water level changes. Binh et al. [6, 30] confirmed that flow changes caused by UHDs have reduced FS water levels in the VMD. Minh et al. [15] revealed the decrease in water level was more pronounced at the upper observation stations of the VMD, with annual reductions ranging from 71.4 to 93.2 mm yr^{-1}.

At Vam Nao, the Pettitt test showed a significant change in 2011, which aligns with the changes observed at Tan Chau. At Vam Nao, the H_{ave} significantly decreased during the FS, reflecting the impact of the regulated flow between the Tien River and the Hau River. On the Hau River, the water level fluctuations at Chau Doc station were recorded in the years 2003, 2007, and 2009, which were quite different from the observation stations. Thus, the upper Mekong floods have a stronger influence on the Tien River than on the Hau River, which is clearly demonstrated through the tests and the data on the distribution of flow rates between the two branches.

The ITA charts (**Figures 9** and **10**) imply the decreasing trend observed in water level features from 1992 to 2023. This is clearly represented by all the data points lying below the 1:1 line, indicating the annual decline in water levels throughout the study period at Tan Chau. In addition, the ITA analysis carried out that the rates of decline are "Medium to High".

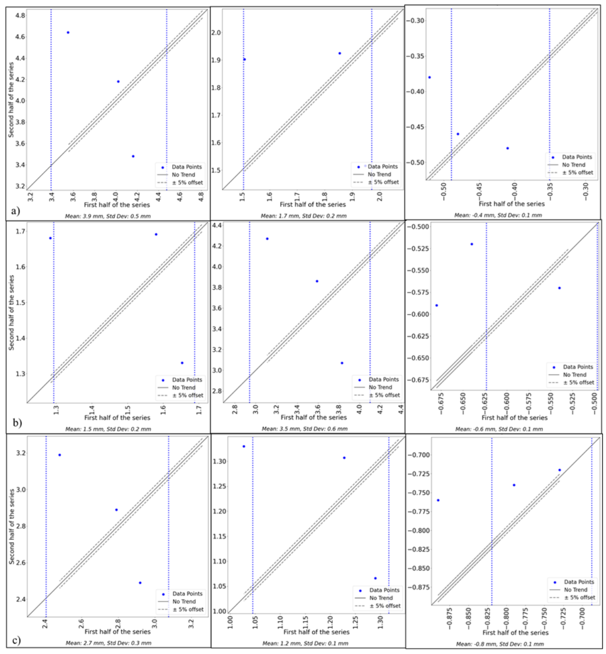

Figure 9. Change trends in annually water levels at Tan Chau (**a**), Chau Doc (**b**), and Vam Nao (**c**) station during the stage 1978–1992 using the ITA.

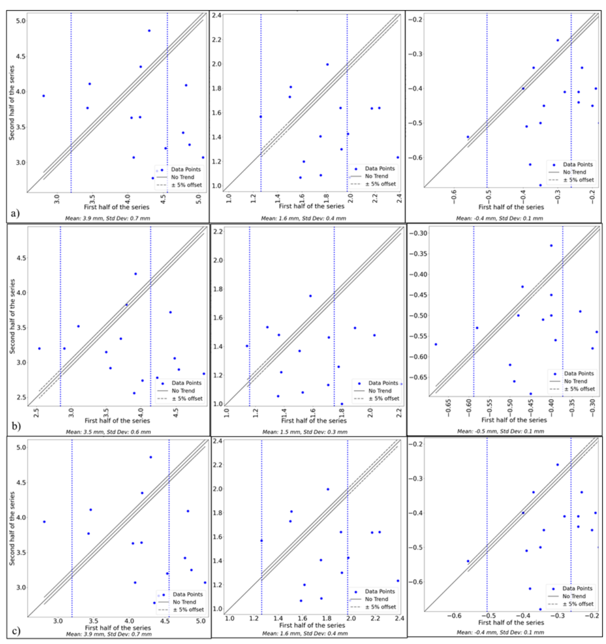

Figure 10. Change trends in annually water levels at Tan Chau (**a**), Chau Doc (**b**), and Vam Nao (**c**) station during the stage 1992–2023 using the ITA.

The results reveal the key role of considering the specific characteristics of each station when analyzing water level trends. While the Vam Nao station showed differences compared to Tan Chau and Chau Doc, it experienced a change in water level behavior around 2011. This suggests that the underlying drivers of the changes in water level behavior may be different at each station.

3.2. Evaluation Results of Flow Discharge Distribution Trends

The study divided the study stages of flow discharge between the Tien and Hau Rivers into 1978–1992, 1993–2011, 2012–2017, and 2018–2023 based on the uniformity of the data series into FS (July to November), DS (January to May), and transitional months (June and December) (**Figure 11**). The results show a clear difference in the flow discharge ratio between Tien and Hau Rivers.

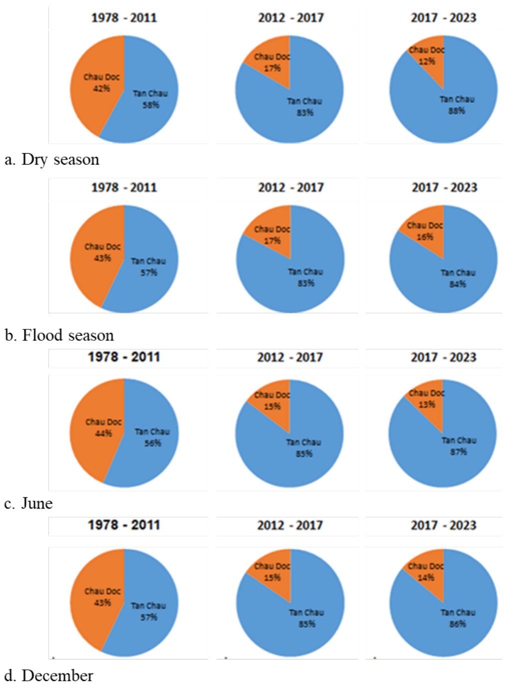

Figure 11. Flow distribution ratio across Tien and Hau Rivers for the periods 1978–1992, 2012–2017, and 2018–2023 in the dry season, FS and transitional months (June and December).

In the DS, the period from 1978 to 1992 showed a relatively balanced flow discharge ratio between Tien and Hau Rivers, with about 42% of the water discharge flowing to Hau River. However, in the 2012–2017 and 2018–2023 periods, the water discharge ratio at Tan Chau station increased significantly, while Chau Doc station recorded a sharp decline. The water discharge ratio flowing to the Hau River in the 2012–2017 and 2018–2023 periods was 17% and 12%, respectively. This reflects a concentration of flow more towards the Tien River during the DS.

In the FS, the change was not as pronounced in the 1978–1992 and 1993–2011 periods, with about 42% of the water discharge flowing to the Hau River, similar to the dry season. However, starting from 2012–2017, the water discharge ratio at Tan Chau station continued to dominate over Chau Doc station. The water discharge ratio to Chau Doc station in the 2012–2017 and 2018–2023 periods was 17% and 16%, respectively. In the transitional months, a similar trend was also observed. The water discharge ratio at Tan Chau station gradually increased over the period, while Chau Doc station decreased. This could reflect changes in the flow distribution due to natural factors and the impact of upstream hydrological works.

4. Conclusions

The work comprehensively analysed the hydrological regime variations between the Tien and Hau Rivers during the period of 1978–2023 under the impacts of anthropogenic and climate change. The results have highlighted significant changes in the hydrological regime between the Tien and Hau Rivers from 1978 to 2023. Prior to 1992, the water levels at the Tan Chau, Chau Doc, and Vam Nao stations remained stable, with no notable trends in the flow discharge and water level. However, after 1992, especially from 2011 onward, the water levels fluctuated noticeably. The flood peak water levels at Tan Chau station decreased at a rate of 41.4 mm yr^{-1}, while both the average and minimum water levels also showed a similar downward trend. In contrast, the dry season water levels showed a slight increase at all three stations, particularly in the early months of the year, reflecting the adjustment of flow due to UHDs.

The flow distribution ratio between the Tien and Hau Rivers also underwent significant changes. Before 1992, the water ratio between Tan Chau and Chau Doc stations was relatively balanced, with about 42% of the water flowing through Hau River. However, since 2011, the water volume has mainly concentrated in the Tien River. The ratio of water flowing through Hau River at Chau Doc station dropped sharply to 16–17% during both the FS and DS, reflecting the dominance of upstream floods in the Tien River. The flow through Vam Nao River was still strongly dominated by the Tien River, especially during the FS.

The study provided a crucial scientific basis to assess and better understand the hydrological regime variations in the VMD. The study highlights the necessity for sustainable water resource management solutions. Cross-border water management cooperation among the countries in the Mekong River basin plays a critical role in minimizing the impacts of unsustainable exploitation and ensuring sustainable development for the region in the background of increasing CC.

Author Contributions

Conceptualization, N.D.Q.H. and T.T.K.; methodology, N.D.Q.H. and T.T.K.; software, N.D.Q.H.; validation, N.D.Q.H., T.T.K. and D.T.A.; investigation, N.D.Q.H.; data curation, N.D.Q.H.; writing—original draft preparation, N.D.Q.H. and T.T.K.; writing—review and editing, D.T.A.; visualization, N.D.Q.H.; supervision, N.D.Q.H. and T.T.; project administration, D.T.A.; funding acquisition, N.D.Q.H. and T.T. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

We encourage all authors of articles published in our journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data was created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Binh, D.V., Kantoush, S., Mai, N.P., et al., 2018. Water level changes under increased regulated flows and degraded river in Vietnamese Mekong Delta. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering). 74(5), 871–876. DOI: https://doi.org/10.2208/jscejhe.74.5_I_871

[2] Duc, T.D., Halsema, G.V., Hellegers, P.J.G.J., et al., 2019. Long-term sustainability of the Vietnamese Mekong Delta in question: An economic assessment of water management alternatives. Agricultural Water Management. 223, 105703. DOI: https://doi.org/10.1016/j.agwat.2019.105703

[3] Anthony, E.J., Brunier, G., Besset, M., et al., 2015. Linking rapid erosion of the Mekong River delta to human activities. Scientific reports. 5(1), 14745. https://doi.org/10.1038/srep14745

[4] Kondolf, G.M., Rubin, Z.K., Minear, J.T., 2014. Dams on the Mekong: Cumulative sediment starvation. Water Resources Research. 50(6), 5158–5169. DOI: https://doi.org/10.1002/2013WR014651

[5] Lu, X.X., Siew, R.Y., 2006. Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. Hydrology and Earth System Sciences. 10(2), 181–195. DOI: https://doi.org/10.5194/hess-18-3033-2014

[6] Hackney, C.R., Darby, S.E., Parsons, D.R., et al., 2020. River bank instability from unsustainable sand mining in the lower Mekong River. Nature Sustainability. 3(3), 217–225. DOI: https://doi.org/10.1038/s41893-019-0455-3

[7] Binh, D.V., Kantoush, S., Sumi, T., 2020. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. Geomorphology. 353, 107011. DOI: https://doi.org/10.1016/j.geomorph.2019.107011

[8] Gierszewski, P.J., Habel, M., Szmańda, J., et al., 2020. Evaluating effects of dam operation on flow regimes and riverbed adaptation to those changes. Science of the Total Environment. 710, 136202. DOI: https://doi.org/10.1016/j.scitotenv.2019.136202

[9] Mai, N.P., Kantoush, S., Sumi, T., et al., 2018. Assessing and adapting the impacts of dams operation and sea level rising on saltwater intrusions into the Vietnamese Mekong Delta. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering). 74(5), 373–378. DOI: https://doi.org/10.2208/jscejhe.74.5_I_373

[10] Hoang, L.P., Vliet, M.T.H.v., Kummu, M., et al., 2019. The Mekong's future flows under multiple drivers:

How climate change, hydropower developments and irrigation expansions drive hydrological changes. Science of the Total Environment. 649, 601–609. DOI: https://doi.org/10.1016/j.scitotenv.2018.08.160

[11] Kim, T.T., Huong, N.T.M., Huy, N.D.Q., et al., 2020. Assessment of the impact of sand mining on bottom morphology in the Mekong River in an Giang Province, Vietnam, using a hydro-morphological model with GPU computing. Water. 12(10), 2912. DOI: https://doi.org/10.3390/w12102912

[12] Lu, X.X., Chua, S.D.X., 2021. River discharge and water level changes in the Mekong River: Droughts in an era of megadams. Hydrological Processes. 35(7), e14265. DOI: https://doi.org/10.1002/hyp.14265

[13] Yun, X., Tang, Q., Wang, J., et al., 2020. Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. Journal of Hydrology. 590, 125472. DOI: https://doi.org/10.1016/j.jhydrol.2020.125472

[14] Anh, L.H., Thong, N., Gratiot, N., et al., 2023. The multi-channel system of the Vietnamese Mekong Delta: Impacts on the flow dynamics under relative sea-level rise scenarios. Water. 15(20), 3597. DOI: https://doi.org/10.3390/w15203597

[15] Minh, H.V.T., Nam, N.D.G., Ngan, N.V.C., et al., 2024. Is Vietnam's Mekong Delta facing wet season droughts?. Earth Systems Environment. 1–33. DOI: https://doi.org/10.1007/s41748-024-00472-3

[16] Park, E., Loc, H.H., Binh, D.V., et al., 2022. The worst 2020 saline water intrusion disaster of the past century in the Mekong Delta: Impacts, causes, and management implications. Ambio. 51(3), 691–699. DOI: https://doi.org/10.1007/s13280-021-01577-z

[17] Eslami, S., Hoekstra, P., Nam, N.T., et al., 2019. Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. Scientific reports. 9(1), 18746. DOI: https://doi.org/10.1038/s41598-019-55018-9

[18] Binh, D.V., Kantoush, S.A., Saber, M., et al., 2020. Long-term alterations of flow regimes of the Mekong River and adaptation strategies for the Vietnamese Mekong Delta. Journal of Hydrology: Regional Studies. 32, 100742. DOI: https://doi.org/10.1016/j.ejrh.2020.100742

[19] Fujihara, Y., Hoshikawa, K., Fujii, H., et al., 2016. Analysis and attribution of trends in water levels in the Vietnamese Mekong Delta. Hydrological processes. 30(6), 835–845. DOI: https://doi.org/10.1002/hyp.10642

[20] Lee, S.K., An, D.T., 2019. Spatio-temporal variations in meteorology drought over the Mekong River Delta of Vietnam in the recent decades. Paddy and Water Environment. 17, 35–44. DOI: https://doi.org/10.1007/s10333-018-0681-8

[21] Jordan, C., Tiede, J., Lojek, O., et al., 2019. Sand mining in the Mekong Delta revisited-current scales of local sediment deficits. Scientific reports. 9(1), 17823. DOI: https://doi.org/10.1038/s41598-019-53804-z

[22] Brunier, G., Anthony, E.J., Goichot, M., et al., 2014. Recent morphological changes in the Mekong and Bassac river channels, Mekong delta: The marked impact of river-bed mining and implications for delta destabilisation. Geomorphology. 224, 177–191. DOI: https://doi.org/10.1016/j.geomorph.2014.07.009

[23] Xue, Z., Liu, J.P., Ge, Q., 2011. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: Connection to damming, monsoon, and ENSO. Earth Surface Processes and Landforms. 36(3), 296–308. DOI: https://doi.org/10.1002/esp.2036

[24] Thanh, N.C., An, D.T., 2024. Assessing water level variability in the Mekong Delta under the impacts of anthropogenic and climatic factors. Journal of Environmental & Earth Sciences. 7(1), 123–131. DOI: https://doi.org/10.30564/jees.v7i1.7355

[25] Yoshida, Y., Lee, H.S., Trung, B.H., et al., 2020. Impacts of mainstream hydropower dams on fisheries and agriculture in lower Mekong Basin. Sustainability. 12(6), 2408. DOI: https://doi.org/10.3390/su12062408

[26] Urban, F., Nordensvärd, J., Khatri, D., et al., 2013. An analysis of China's investment in the hydropower sector in the Greater Mekong Sub-Region. Environment, Development Sustainability. 15, 301–324. DOI: https://doi.org/10.1007/s10668-012-9415-z

[27] Bao, J., Twardek, W.M., Zhang, C., et al., 2023. Mitigating the cumulative effects of hydropower and climate change on riverine fishes. Reviews in Fish Biology Fisheries. 33(4), 915–930. DOI: https://doi.org/10.1007/s11160-023-09766-7

[28] Cho, M.S., Qi, J., 2023. Characterization of the impacts of hydro-dams on wetland inundations in Southeast Asia. Science of the Total Environment. 864, 160941. DOI: https://doi.org/10.1016/j.scitotenv.2022.160941

[29] Anh, T.T., Pittock, J., Duc, T.D., 2020. Adaptive flood governance in the Vietnamese Mekong Delta: A policy innovation of the North Vam Nao scheme, An Giang Province. Environmental Science Policy. 108, 45–55. DOI: https://doi.org/10.1016/j.envsci.2020.03.004

[30] Binh, D.V., Kantoush, S.A., Sumi, T., et al., 2021. Effects of riverbed incision on the hydrology of the Vietnamese Mekong Delta. Hydrological Processes. 35(2), e14030. DOI: https://doi.org/10.1002/hyp.14030

[31] Li, D., Long, D., Zhao, J., et al., 2017. Observed changes in flow regimes in the Mekong River basin. Journal of Hydrology. 551, 217–232. DOI: https://doi.org/10.1016/j.jhydrol.2017.05.061

[32] Winemiller, K.O., McIntyre, P.B., Castello, L., et al., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science. 351, 128–129. DOI: https://doi.org/10.1126/science.aac7082

[33] Sun, H., He, D., Sui, X., et al., 2020. Predicting impacts of future climate change and hydropower develop-

ment towards habitats of native and non-native fishes. Science of the Total Environment. 707, 135419. DOI: https://doi.org/10.1016/j.scitotenv.2019.135419

[34] Binh, D.V., Kantoush, S.A., Ata, R., et al., 2022. Hydrodynamics, sediment transport, and morphodynamics in the Vietnamese Mekong Delta: Field study and numerical modelling. Geomorphology. 413, 108368. DOI: https://doi.org/10.1016/j.geomorph.2022.108368

[35] Lee, S.K., An, D.T., 2020. Extreme rainfall trends over the Mekong Delta under the impacts of climate change. International Journal of Climate Change Strategies and Management. 12(5), 639–652. DOI: https://doi.org/10.1108/IJCCSM-04-2020-0032

[36] Khuong, T.H., Menenti, M., Jia, L., 2022. Surface water mapping and flood monitoring in the Mekong Delta using sentinel-1 SAR time series and Otsu threshold. Remote Sensing. 14(22), 5721. DOI: https://doi.org/10.3390/rs14225721

[37] Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. Journal of the Royal Statistical Society: Series C (Applied Statistics). 28(2), 126–135. DOI: https://doi.org/10.2307/2346729

[38] Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. Journal of Hydrology. 259(1–4), 254–271. DOI: https://doi.org/10.1016/S0022-1694(01)00594-7

[39] Wang, F., Shao, W., Yu, H., et al., 2020. Re-evaluation of the power of the Mann-Kendall test for detecting monotonic trends in hydrometeorological time series. Frontiers in Earth Science. 8(14), 1–12. DOI: https://doi.org/10.3389/feart.2020.00014

[40] Coen, M.C., Andrews, E., Bigi, A., et al., 2020. Effects of the prewhitening method, the time granularity, and the time segmentation on the Mann–Kendall trend detection and the associated Sen's slope. Atmospheric measurement techniques. 13(12), 6945–6964. DOI: https://doi.org/10.5194/amt-13-6945-2020

[41] Meena, M., 2020. Rainfall statistical trend and variability detection using Mann-Kendall test, Sen's slope and coefficient of variance—A case study of Udaipur district (1957–2016). Applied Ecology and Environmental Sciences. 8(1), 34–37. DOI: https://doi.org/110.12691/aees-8-1-5

[42] Kendall, M., 2015. Trend analysis of Pahang river using non-parametric analysis: Mann Kendall's trend test. Malaysian Journal of Analytical Sciences. 19(6), 1327–1334.

[43] Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association. 63(324), 1379–1383. DOI: https://doi.org/10.1080/01621459.1968.10480934

[44] Aswad, F.K., Yousif, A.A., Ibrahim, S.A., 2020. Trend analysis using Mann-Kendall and Sen's slope estimator test for annual and monthly rainfall for Sinjar district, Iraq. Journal of Duhok University. 23(2), 501–508.

[45] Şen, Z., 2012. Innovative Trend Analysis Methodology. Journal of Hydrologic Engineering. 17(9), 1042–1046. DOI: https://doi.org/10.1061/(ASCE)HE.1943-5584.0000556