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ARTICLE

Assessing Water Level Variability in the Mekong Delta under the Impacts of Anthropogenic and Climatic Factors

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ABSTRACT

In recent years, the water level in the Mekong Delta (MD) has undergone changes, attributed to the impacts of anthropogenic activities and climate change. Declining water levels have had implications for various aspects of life and aquatic ecosystems in the lower basin water bodies. Analyzing long-term trends in rainfall and water levels is crucial for enhancing our understanding. This study aims to examine the evolving patterns of water level and rainfall in the region. Data on water levels and rainfall from observation stations were gathered from the National Center for Hydrometeorological Forecasting, Vietnam, spanning from 2000 to 2014. The assessment of homogeneity and identification of trend changes were conducted using the Standard Normal Homogeneity Test (SNHT) and the Mann-Kendall test. The results indicate that changes in water levels at the Tan Chau and Chau Doc stations have been observed since 2010 due to the operation of flow-regulating structures in the upper Mekong River. Following the commencement of upstream dam operations, the water level at the headwater stations of the Mekong River has been higher than the long-term average during the dry season and lower than the average during the flood season. The study findings highlight the influence of altered rainfall patterns under the impact of climate variability (ICC) on water level trends in the study area. While rainfall plays a significant role in increasing water levels during the flood season, the operation of hydropower dams (UHDs) stands out as the primary

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factor driving water level reductions in the study area.

Keywords: Mekong Delta; Hydropower; Water Level; Local Rainfall; Climate Variability

1. Introduction

The Mekong River (MR), one of the world's ten largest rivers, plays a crucial role in Southeast Asia's hydrology and ecosystems [1, 2]. Originating from the Tibetan Plateau, it traverses six countries before reaching the MD, covering a basin area of 795,000 km² with a mainstream length of approximately 4,800 km [3, 4]. The river's hydrological regime is increasingly influenced by both anthropogenic activities and climatic factors, presenting a complex challenge for water resource management and environmental sustainability in the basin [5, 6].

Recent studies have highlighted significant alterations in the Mekong River Basin's (MRB) flow regime, primarily attributed to the construction and operation of UHDs [3, 6]. Dang, Cochrane and Arias [7] reported that an increase in flow discharges in the dry season and a decrease in flow discharges during the flood season, with flow discharges in the dry season at Kratie station increasing by 25–160% compared to the 1982–1992 period. However, the Mekong River Commission [1] estimated a more conservative change of approximately 12% of flow discharges in the dry season at Kratie, highlighting the need for further investigation into these discrepancies. Recent climatic phenomenon has highlighted the delta's vulnerability to hydrological extremes [8, 9].

Notably, anthropogenic factors significantly influence the MRB's hydrology [10, 11]. The hydrological impacts of UHDs extend beyond immediate flow alterations [3, 10]. Cochrane, Arias and Piman [12, 13] observed water level changes at upstream stations since 1991, emphasizing the need for comprehensive studies on downstream effects, particularly in the MD. The Tonle Sap Lake system plays a critical role in moderating these impacts, acting as a natural flow regulator for the lower Mekong River [3, 5]. Recent analyses by Triet, Dung and Fujii [14] and Xue et al. [12] indicate a 7–11.9% increase in the proportion of flow discharges in the dry season at Kratie station from 1990 to 2016, suggesting a shift in the seasonal water balance. Besides, climatic variables also play a crucial role in the change of hydrological mechanisms, especially water level [3, 5]. For instance, during the 2016 dry season, the influence of the El-Niño event resulted in abnormally low water levels across all observation stations in the MD [1, 2]. Water levels over the entire MD in December and January were significantly below the 1980–2013 average, underscoring the region's sensitivity to large-scale climatic oscillations [2, 10]. The combined effects of UHDs and climate change on the MD's flow regime remain a subject of attention from the scientific community [3, 14]. Kantoush et al. [3] observed a decreasing trend in flow discharge, attributing it primarily to UHDs, while also acknowledging the contribution of climate-induced droughts, particularly from 2010 to 2016 [6, 13]. Delgado, Merz and Apel [7] recorded a strong correlation between monsoon intensity and the Mekong's flood regime, with 80–90% of the lower MD's annual discharge occurring during the rainy season.

The complex interplay between the delta's hydrological systems, climatic factors, and anthropogenic influences presents a multifaceted challenge for sustainable resource management. As upstream developments and climate change continue to alter the Mekong River's flow regime, there is an urgent need for comprehensive research to quantify and predict water level variability in the delta [1, 4]. Such understanding is crucial for developing adaptive strategies to maintain the delta's ecological integrity and support its vital role in regional food security and socio-economic development.

Given the intricate relationship between anthropogenic activities and climatic factors in shaping the MD's hydrology, this study aims to quantify and differentiate their respective impacts on water level variability in the region. By employing advanced statistical analyses and hydrological modeling, we seek to provide a comprehensive assessment of these influences, contributing to improved water resource management strategies and climate adaptation policies in the MD.

2. Materials and Method

2.1. Study Area

The MD, a critical component of the lower Mekong River, encompasses an area of approximately 39,000 km² extending from the Vietnam-Cambodia border to the East Sea (**Figure 1**). This complex hydrological system is characterized by the division of the Mekong River into two primary branches, the Tien and Hau Rivers, which further diverge into eight major estuaries: Tieu, Dai, Ba Lai, Ham Luong, Cung Hau, Co Chien, Dinh An, and Tran De[2, 13]. The delta's hydrodynamics are intricately linked to upstream processes, with the Tonle Sap Lake playing a crucial role in regulating dry season flow into the region[12, 15]. Often referred to as Vietnam's "rice bowl", the delta boasts a cultivated area of approximately 4.0 million hectares[16, 17]. Of this, over 2.6 million hectares are dedicated to agricultural production, contributing more than 52% to Vietnam's total food production[1, 13]. This agricultural productivity is intrinsically linked to the delta's hydrological regime, highlighting the critical importance of understanding and managing water level variability in the region[18, 19].

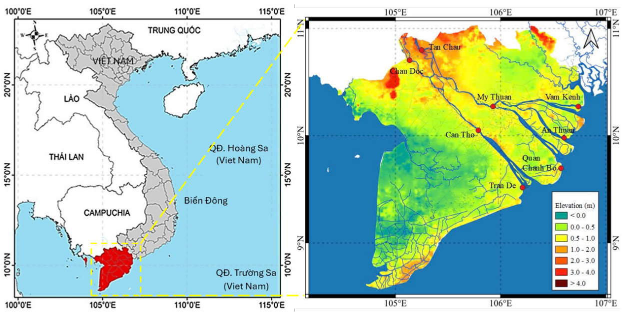

Figure 1. Topographic map of the study area with water level stations marked in red circles.

2.2. Water Level and Rainfall Data Collection

Daily water level and rainfall data series at the eight observation stations located in the Mekong Delta were obtained from the South Region Hydrology-Meteorology Centre of Vietnam (**Table 1**, **Figure 1**). Both water level and rainfall data have been verified through interruption points detection.

2.3. Approach Methods

2.3.1. Quality Assessment of Rainfall and Water Level Data Series

To avoid interruption of observed data series, the study used the Standard Normal Homogeneity Test (SNHT) method to assess the quality of rainfall and water level data series at observation stations across the study area[16, 19]. The SNHT is a statistical method employed to assess the homogeneity of climatological time series data[16, 20]. This technique is particularly useful for detecting discontinuities or shifts in data that may arise from various factors, such as changes in measurement practices, instrument calibrations, or environmental influences[20]. The SNHT method operates by comparing the mean of the entire dataset to the mean of a subset of data, allowing researchers to identify any significant deviations that indicate non-homogeneous conditions[16, 19]. By applying the SNHT, researchers can establish a standardized metric to evaluate the consistency of time series data, thereby enhancing the reliability of climatic analyses. This method is widely utilized in climatology and hydrology, making it an essential tool for researchers aiming to ensure the integrity of their data when studying long-term trends in climate variability and related phenomena[16, 21]. Its robustness and efficiency make it a preferred choice for homogenizing climate records[19, 21]. The SNHT is defined by Equation (1):

$$T_s = \max T_m, \ \ with \ 1 \le m \ \le n \tag{1}$$

To define the discontinuity data points, which relate to the value points when Ts reaches the maximum value in the observation data series. Where, Tm in Equation (1) is defined by Equation (2):

$$\begin{aligned} T_m \ &= \bar{m}\ z_1 + \ (n-m)\ \bar{z}_1, \\ with\ \ m \ &= \ 1,\ 2,\ 3, \ldots.., n \end{aligned} \tag{2}$$

And $z_1$in Equation (2) is defined by Equation (3):

$$z_1 = \frac{1}{m} \sum\nolimits_{1\,=\,1}^{n} \frac{\left(M_i - \bar{M}\right)}{s} \tag{3}$$

Where m and s in Equation (3) are the mean value and standard deviation of the data series.

2.3.2. Change Trend Detection

To detect the change trends in the water level and rainfall data series, a non-parametric statistical method namely the Mann-Kendall test is used for detecting data series during the period 1984–2018 at some observation stations across the study areas. The Mann-Kendall test is a non-parametric statistical method widely used to analyze trends in time series data, particularly in climatology, hydrology, and environmental studies[22, 23]. This test is designed to identify monotonic trends (increasing or decreasing) of observation data series[23, 24]. The Mann-Kendall test is based on comparing the ranks of data points over time, allowing researchers to

Table 1. Basic characteristics of rainfall and water level observation stations.

No.	Station	Latitude (N)	Longitude (E)	Elevation (m)	Data Type	
					Rainfall	Water Level
1	Tan Chau	10.8006	105.2480	2.89	x	x
2	Chau Doc	10.7053	105.1340	1.61	x	x
3	My Thuan	10.2750	105.9260	1.04	x	x
4	Can Tho	10.0528	105.7870	0.91	x	x
5	Vam Kenh	10.2744	106.7370	0.92		x
6	An Thuan	9.9811	106.6020	0.99		x
7	Tran De	9.5150	106.2070	0.86		x
8	Quan Chanh Bo	9.6951	106.5725	1.19		x

detect significant trends even in the presence of seasonal variations or outliers[22, 24, 25]. One of the key advantages of the Mann-Kendall test is its robustness, as it does not require the data to follow a normal distribution, making it suitable for diverse datasets[16, 19]. Additionally, the test can be applied to both continuous and categorical data, enhancing its versatility. The results of the Mann-Kendall test provide valuable insights into long-term changes in temperature, precipitation and water level, helping researchers and policymakers understand trends and make informed decisions regarding environmental management[19, 23]. Accordingly, the Mann-Kendall test assumes a null hypothesis (H_0) of no trend existing while the monotonic trends as increasing or decreasing are defined based on the alternative hypothesis (H_1)[16]. The Mann-Kendall test is defined by Equation (4):

$$S = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \operatorname{sgn}(X_j - X_i) \tag{4}$$

Where $\operatorname{sgn}(X_j - X_i)$ is obtained by Equation (5):

$$\operatorname{sgn}(X_j - X_i) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases} \tag{5}$$

In a time series, X_i, i = 1, 2, 3, …, n, the discrepancy of statistics (S) is assumed to be a normal distribution, and S is defined by Equation (6):

$$\operatorname{var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{j=1}^{m} t_j (t_j - 1)(2t_j + 5) \right] \tag{6}$$

and the standard test (Zs) is commonly applied to detect the change trends in the input data series. The Zs is given by Equation (7):

$$Zs = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases} \tag{7}$$

Basically, if the value of Zs is positive, a normalized test statistic reflects the increasing trend, while if the value of Zs is negative a normalized test statistic reflects the decreasing trend.

3. Results and Discussion

3.1. Change in Rainfall Features in the Stage 2000–2014

Analysis of the rainfall data series from 2000 to 2014 at Tan Chau and Chau Doc stations (two stations in the upstream Hau and Tien Rivers) is shown in **Figure 1**. For Tan Chau station, analyzed results pointed out that annual rainfall during the stage of 2000–2008 was higher than the average annual rainfall, except for the years of 2002, 2004, and 2006, which were lower than the average annual rainfall. The main reason may be caused by the occurrence of El-Nino phenomena (**Figures 2** and **3**; **Table 2**).

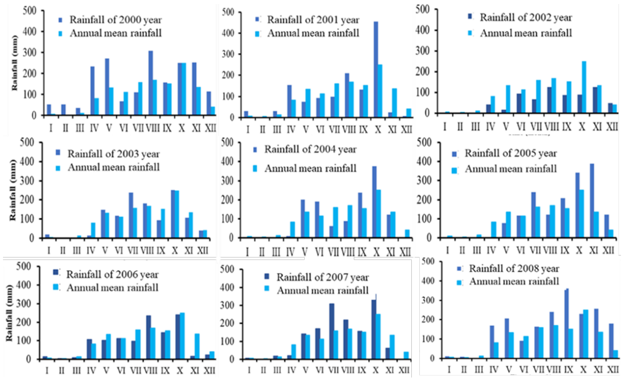

Figure 2. Change in rainfall at Tan Chau station in the stage 2000–2008.

In these years, the total rainfall in the rainy season is lower than the total rainfall for many average years because of the occurrence of the El-Nino phenomenon. While in the years of 2000, 2001, 2007, 2008, and 2010, the study area recorded the occurrence of the La-Nina phenomenon, study area; therefore, the study area recorded higher annual rainfall than the average annual rainfall during the stage of 2000–2014.

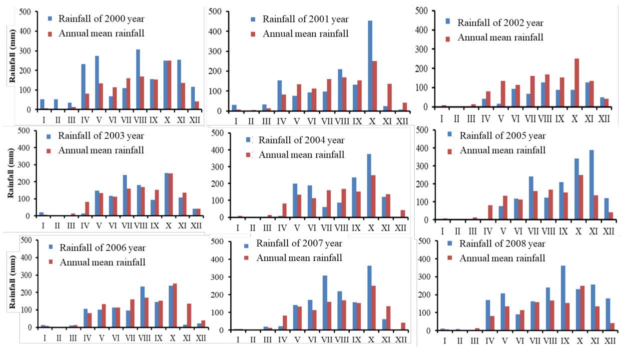

Figure 3. Change in rainfall at Chau Doc station in the stage 2000–2008.

For Chau Doc station, analyzed results also indicated that annual rainfall during the stage of 2000–2008 was recorded higher than the average annual rainfall, except for the years of 2002 and 2004. The main reason may be caused by the occurrence of El-Nino phenomena (**Table 1**). Specifically, the rainfall in the rainy season during the stage of 2000–2008 is lower than the average annual rainfall during the period of 2000–2014 because of the occurrence of El-Nino phenomenon. While in the years 2000, 2001, 2007, 2008 and 2010, the study area recorded the occurrence of La-Nina phenomenon, rainfall in the rainy season of these years is recorded higher than the average annual rainfall (**Table 1**).

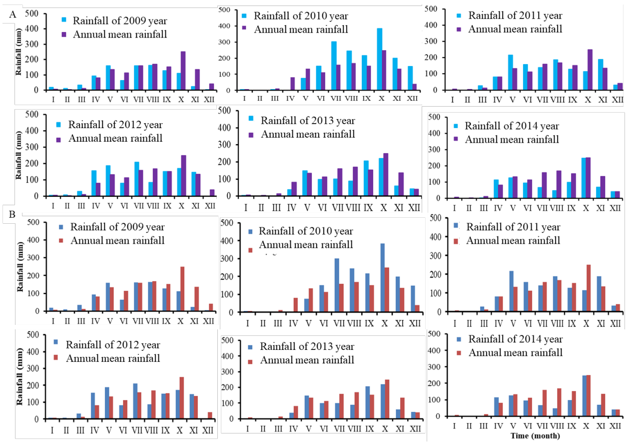

Figure 4. Change in rainfall at (**a**) Tan Chau station and (**b**) Chau Doc station in the stage of 2009–2014.

For the stage of 2009–2014, the years of 2009 and 2014 recorded lower rainfall than the average annual rainfall (**Figure 4**). The main reason may be the occurrence of El-Nino phenomenon, whereas in the year of 2010, the occurrence of La-Nina phenomenon led to higher rainfall than the average annual rainfall, while in the remaining years, rainfall in the rainy season is equivalent to the average annual rainfall.

3.2. Temporal Variations of Water Level Characteristics at Tan Chau and Chau Doc Upstream Stations in the Stage 2000–2014

Analysis of water level data series from 2000 to 2014 at Tan Chau and Chau Doc stations is also shown in **Figure 5**. Results indicated that the water level in the dry season (January–April) of the stage 2000–2008 was lower than the average water level of the stage 1980–1999, while in the flood season, the water level was higher than the average water level of the stage 1980–1999 at Tan Chau station and Chau Doc station (**Figure 5**). Analysis of water level data series in the stage of 2010–2014 at both Tan Chau and Chau Doc stations also showed that the water level in the dry season was recorded lower than the mean water level of the stage 1980–1999 while these values in the flood season were higher than the mean water level of the stage 1980–1999. The analyzed results of the water level data series can be confirmed when two upstream hydropower dams (e.g., Jinghong and Nam Theun) were put into operation in the stage 2010–2014 the water level in the dry season at both Tan Chau and Chau Doc stations recorded a tendency to be higher than the average water level of the stage 1980–1999, while the water level during the flood season months is always lower than the average water level of the period 1980–1999. It can be affirmed that this is a sign of the regulation of flow from upstream hydropower dams. Analyzed results proved that the upstream hydropower dams have contributed significantly to the flow regime at the Mekong Delta.

Generally, climate factors contribute to the variation of water level across the study area; however, these contributions are not significant. Through analysis results, it can be affirmed that the upstream hydropower dams have significantly contributed to the variation of flow regime in the Mekong Delta, especially in the period 2010–2014 when the Jinghong dam in China and Nam Theun-2 dam in Laos were put into operation. However, our study has not considered the influence of tides propagating from the East Sea

Table 2. Operation periods of typical ENSO events across the study area.

Period	El-Nino		Duration (Month)	Period	La-Nina		Period (Month)
	Onset	End			Onset	End	
2002–2003	June 2002	Mar 2003	10	1998–2001	June 1998	Feb 2001	10
2004–2005	July 2004	Apr 2005	10	2007–2008	Aug 2007	Jun 2008	10
2006–2007	Sep 2006	Jan 2007	5	2010–2012	Jul 2010	May 2012	5
2009–2010	July 2009	Apr 2010	10	2018–2019	June 2017	Sep 2018	15
2014–2016	Nov 2014	May 2016	7	2021–2022	Feb 2021	Nov 2022	21

to upstream locations (Tan Chau and Chau Doc stations), which may contribute to the increase in monthly mean water level values during the dry and flood seasons. Those tidal effects intruding into the inner parts of the Mekong Delta have been figured out by the study of Eslami, Hoekstra, and Nguyen Trung[19], where they showed the application of the amplitude of the M2 tidal constituent during the period since 2000.

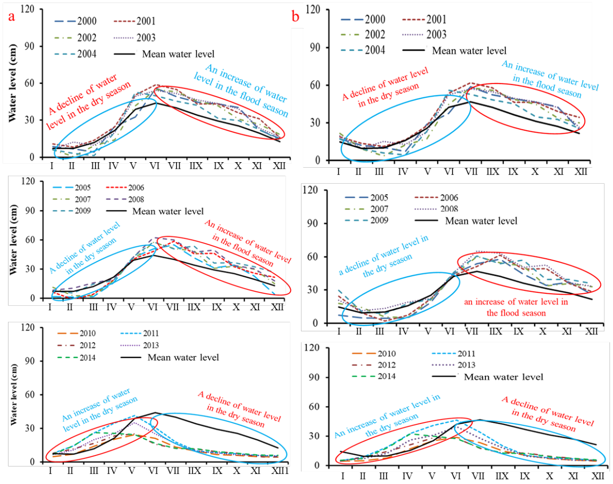

Figure 5. Change in water level at (**a**) Chau Doc station and (**b**) Tan Chau station in the stage of 2000–2014.

3.3. Temporal Trends of Water Level Characteristics at Tan Chau and Chau Doc Upstream Stations in the Stage 2000–2014

Table 3 presents the water level characteristics at two upstream stations, Tan Chau and Chau Doc, over the period of 2000–2014. At Tan Chau station, the average water level fluctuated between 130 and 238, with the lowest recorded level of –56 and the highest at 506 (**Figure 6a**). The trend indicates a general decrease in the average water level over time. The occurrence dates of extreme levels varied throughout the years, indicating the dynamic nature of water levels at this station. Conversely, at Chau Doc station, the average water level ranged from 113 to 219, with the lowest recorded level of –68 and the highest at 490. Similar to Tan Chau station, there is an overall decreasing trend in the average water level at Chau Doc. The dates of extreme water levels also varied annually, showcasing the variability in water level patterns at this station (**Figure 6a**). Overall, the data reveals a complex interplay of factors influencing water levels at the Tan Chau and Chau Doc stations, with both stations experiencing a downward trend in average water levels.

The minimum water level at Tan Chau station shows a general downward trend, with a decrease from −18 cm in 2000 to −26 cm in 2014. In contrast, the minimum water level at Chau Doc station shows a more pronounced downward trend, with a decrease from −28 cm in 2000 to −33 cm in 2014. The minimum water level at both stations exhibits a cyclical pattern, with extreme lows occurring in the early 2000s and early 2010s. The extreme low at Tan Chau station occurred in 2005, with a value of −56 cm, while at Chau Doc station this value was −68 cm (**Figure 6c**). The trend changes at both stations suggest that the minimum water level is influenced by a combination of natural and anthropogenic factors, including changes in precipitation and water usage patterns.

The maximum water level at Tan Chau station shows a general downward trend, with a decrease from 506 cm in 2000 to 394 cm in 2014. The maximum water level at Chau Doc station also shows a downward trend, with a decrease from 490 cm in 2000 to 320 cm in 2014. The maximum water level at both stations exhibits a cyclical pattern, with extreme highs occurring in the early 2000s and early 2010s. The extreme high at Tan Chau and Chau Doc stations occurred in 2001, with values of 506 cm and 490 cm (**Figure 6b**). The trend changes at both stations suggest that the maximum water level is also dominated by a combination of natural and anthropogenic factors, including changes in precipitation and water usage patterns. The results indicate that the maximum water level at both stations has decreased significantly over

Table 3. Basic statistical characteristics of water level at two Tan Chau and Chau Doc upstream stations in the period 2000–2014.

Year	Tan Chau Station					Chau Doc Station				
	Mean (cm)	**Min (cm)**	**Occurred Date**	**Max (cm)**	**Occurred Date**	**Mean (cm)**	**Min (cm)**	**Occurred Date**	**Max (cm)**	**Occurred Date**
2000	238	−18	28-Apr	506	23-Sep	219	−28	28-Apr	490	23-Sep
2001	223	−25	16-May	478	20-Sep	202	−29	16-May	448	23-Sep
2002	217	−23	22-May	482	29-Sep	188	−40	22-May	442	30-Sep
2003	158	−24	13-Apr	405	26-Sep	135	−41	13-Apr	350	29-Sep
2004	163	−38	01-Apr	441	28-Sep	141	−50	01-Apr	402	29-Sep
2005	175	−56	18-May	435	20-Sep	153	−68	18-May	390	21-Sep
2006	175	−34	07-May	417	17-Sep	150	−47	07-May	371	21-Oct
2007	161	−35	26-May	408	23-Sep	138	−46	25-May	356	24-Oct
2008	181	−35	02-Apr	377	01-Sep	153	−51	02-Apr	320	01-Oct
2009	173	−51	20-Apr	412	11-Oct	148	−68	20-Apr	352	14-Oct
2010	130	−40	09-Apr	320	24-Oct	113	−53	09-Apr	282	14-Oct
2011	200	−41	12-May	486	30-Sep	175	−56	12-May	427	12-Oct
2012	143	−40	14-May	325	02-Oct	126	−58	30-Apr	290	17-Oct
2013	164	−45	21-Apr	435	03-Oct	146	−49	20-Apr	383	08-Oct
2014	157	−26	06-Jun	394	13-Aug	140	−33	06-Jun	320	15-Aug

the 15-year period, with a decline of 112 cm at Tan Chau station and 170 cm at Chau Doc station.

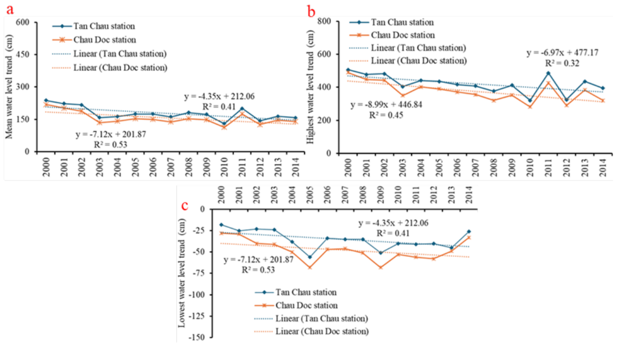

Figure 6. Change trend in (**a**) mean water level, (**b**) maximum water level and (**c**) minimum water level at Tan Chau and Chau Doc stations during the period 2000–2014.

These change trends suggest that further research is needed to understand the underlying causes of these changes and to develop effective management strategies to mitigate the impacts of drought and water scarcity[26]. Our results are consistent with a study on water-level changes along the Saigon-Dong Nai River Estuary and the East Sea coastline of the Mekong Delta conducted by Thanh, Klaus and Klaus[27].

3.4. Limitations of the Study

The limitation of this study relying solely on water level data is the lack of consideration for the interactions between flow discharge from the upstream of the Mekong River and tidal fluctuations from the East and West Seas. This oversight may lead to an incomplete understanding of water level variability. Without separating these influences, the analysis risks attributing changes in water levels solely to anthropogenic or climatic factors, potentially masking the effects of natural hydrodynamic processes. Such an approach could skew results and hinder accurate predictions, ultimately affecting water management strategies and conservation efforts in the Mekong Delta.

4. Conclusions

The study comprehensively analysed the variation of water levels at two upstream stations in the Mekong Delta from 2000 to 2014, focusing on the impacts of anthropogenic and climatic factors. The findings from the rainfall data series revealed that rainfall had a negligible effect on water level changes at the surveyed stations. Specifically, during El Niño years, increased rainfall correlated with a decrease in flow discharge, while La Niña years resulted in enhanced flow discharge due to higher rainfall levels.

Additionally, the water level analysis indicated significant trends before and after the operational commencement of the Jinghong and Nam Theun-2 dams. From 2000 to 2009, the dry season water levels (December to April) consistently fell below the mean water levels recorded between 1980 and 1999. In contrast, during the flood season (May to November), water levels were markedly higher than the long-term average (1980–1999) for the same period.

However, following the initiation of dam operations in 2010, the dynamics changed. The water levels during the dry season at the Tan Chau and Chau Doc stations rose above the long-term average, indicating an alteration in hydrological patterns due to human intervention. Conversely, the rainy season exhibited a downward trend in water levels compared to the historical average. These findings underscore the complex interplay between climatic variability and anthropogenic influences, highlighting the need for adaptive water management strategies in the Mekong Delta to mitigate the impacts of these changes on local ecosystems and communities.

Author Contributions

D.T.A. and N.C.T. designed the manuscript; D.T.A. and N.C.T. collaborated closely in all aspects of the manuscript preparation. The two authors jointly designed the study and performed a comprehensive analysis of the data. Throughout the research process, D.T.A. and N.C.T. engaged in discussions to interpret the results, ensuring a thorough understanding of the findings. Furthermore, they contributed to the preparation and critical review of the manuscript, enhancing its clarity and rigor. D.T.A. and N.C.T. reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study have been generated but are not currently available in a public repository. The data can be made available by the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. We confirm that the research was conducted independently, without any financial or personal relationships that could have influenced the study's outcomes. This includes any affiliations or funding sources that might be perceived as influencing the integrity of the research. The authors are committed to maintaining transparency and objectivity throughout the research process.

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