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Assessment of Surface Water Quality for Aquaculture Suitability in the Mekong Delta: Spatiotemporal Analysis Using Kruskal–Wallis, Dunn's Test, and PCA at Four Monitoring Stations (2013–2024) †

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Abstract

This study assesses spatiotemporal variation in surface water quality in the Tien–Hau river system, Mekong Delta, Vietnam, using data from four monitoring stations (Tan Chau, Chau Doc, My Thuan, and Can Tho) during 2013–2024. Twelve physicochemical parameters were analysed monthly. Kruskal–Wallis tests showed significant spatial differences in DO, pH, PO_4^{3-}, NO_2^{-}, and NO_3^{-}, while Dunn's test indicated generally better water quality at the upstream station Tan Chau. PCA extracted four components explaining 60.5% of total variance, representing organic enrichment, hydrological dynamics, nutrient runoff, and salinity intrusion. A custom Aquaculture Water Suitability Index (AWSI) based on eight key parameters classified water quality into five suitability levels. Dry season conditions were generally more favourable than rainy-season conditions. Tan Chau in the dry season reached the Excellent class (96.1), whereas rainy-season conditions were less suitable because of high suspended solids. The results support seasonal aquaculture planning in the Mekong Delta.

Keywords: Mekong Delta; surface water quality; aquaculture suitability; Kruskal–Wallis test; PCA; AWSI; spatiotemporal analysis; *Pangasianodon hypophthalmus*; *Penaeus monodon*; QCVN 08:2023/BTNMT

1. Introduction

The Mekong Delta is Vietnam's main agricultural and aquaculture region. The Tien and Hau rivers supply water for irrigation and aquaculture and therefore strongly influence regional livelihoods and food production.

Surface water quality in the delta is under pressure from agriculture, aquaculture effluents, domestic and industrial discharge, urbanisation, and climate-driven hydrological change. These pressures are commonly expressed through nutrient enrichment, organic loading, suspended solids, and increasing salinity intrusion.

Long-term monitoring is needed to detect trends and support management, but multi-parameter datasets require methods that can handle non-normal environmental data [1].

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Kruskal–Wallis and Dunn's tests are suitable for spatial comparison, while PCA helps identify dominant pollution patterns and likely source groups [2–4].

Although previous studies have reported water-quality variation in the Mekong Delta [5–7], fewer studies have combined long-term spatial analysis, multivariate source interpretation, and aquaculture-oriented assessment in a single framework.

Therefore, this study aims to: (i) describe spatiotemporal variability of twelve parameters at four stations from 2013 to 2024; (ii) test spatial and seasonal differences; (iii) identify dominant pollution patterns using PCA; and (iv) evaluate aquaculture suitability using AWSI with reference to QCVN 08:2023/BTNMT [8] and aquaculture standards [9,10].

2. Materials and Methods

2.1. Study Area and Monitoring Network

The study covered the Tien and Hau rivers in the Mekong Delta, Vietnam. Four stations were selected along an upstream–downstream gradient (Figure 1): Tan Chau near the Cambodian border, Chau Doc, My Thuan in the mid-delta, and Can Tho in the lower delta.

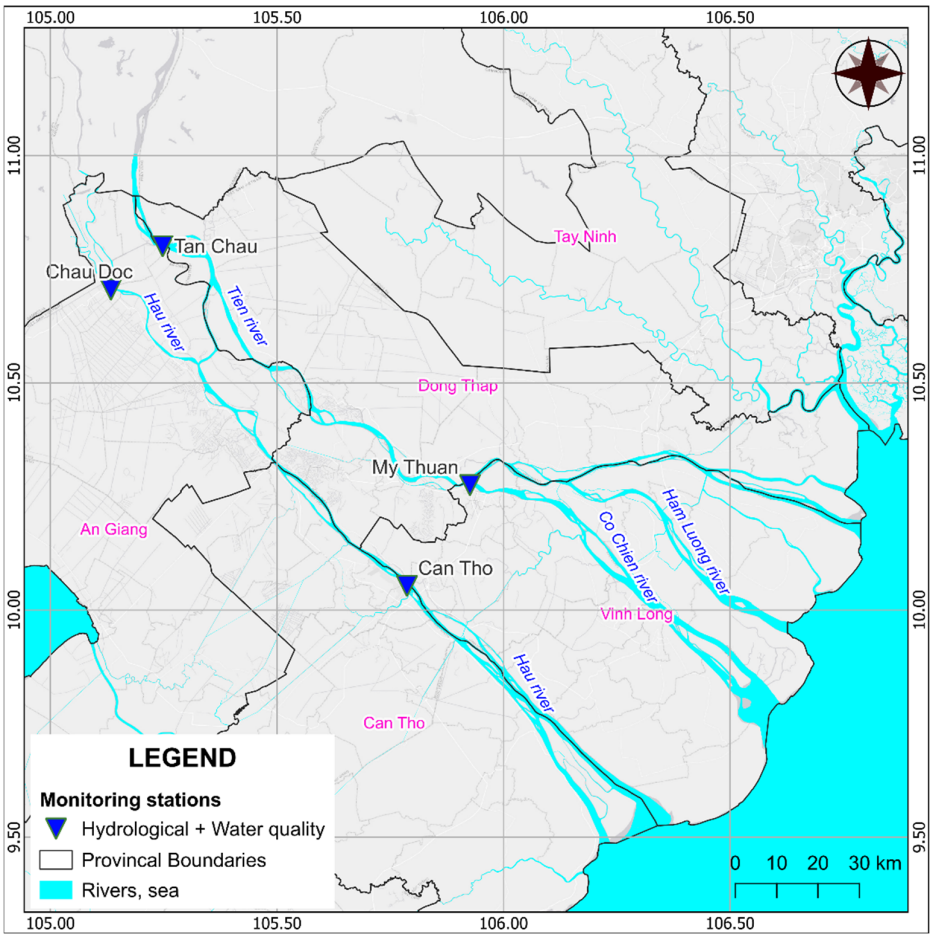


Figure 1. Location of water quality monitoring stations along the Tien–Hau river system, Mekong Delta, Vietnam. Stations represent an upstream–downstream spatial gradient from the Cambodian border (Tan Chau) to the lower delta (Can Tho).

2.2. Data Collection

Water quality was sampled monthly on the 15th day of each month at 07:00 local time, at 50 cm below the surface. Twelve parameters were measured: DO, pH, temperature,

EC, TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and Cl^-. Supplementary spring- and neap-tide samples were collected to capture tidal effects. The dataset spans January 2013 to December 2024, with 135–152 observations per parameter per station. No data were available for 2019. The dry season was defined as December–May and the rainy season as June–November.

2.3. Statistical Methods

2.3.1. Kruskal–Wallis Test

Spatial differences among the four stations were assessed using the Kruskal–Wallis H test [3], a non-parametric alternative to one-way ANOVA. Significance was set at $\alpha = 0.05$, with Bonferroni correction across the twelve parameters. Seasonal differences (dry & rainy) at each station were tested with the two-sided Mann-Whitney U test, and within-season variability was expressed as the coefficient of variation (CV, %).

2.3.2. Dunn's Post Hoc Test

For parameters with significant Kruskal–Wallis results, pairwise station differences were evaluated using Dunn's test [2] with Bonferroni correction.

2.3.3. Principal Component Analysis

PCA was applied to the standardised dataset to identify latent pollution factors. All twelve parameters were included, and samples with missing values were removed (list-wise deletion, n = 558 of 594). Components with eigenvalues > 1 were retained, and loadings ≥ |0.60| were used for interpretation [11].

2.3.4. Aquaculture Water Suitability Index (AWSI)

The Aquaculture Water Suitability Index (AWSI) is a custom composite index developed to evaluate surface-water suitability for aquaculture. Eight parameters (DO, pH, BOD_5, COD, TSS, NH_4^+, NO_2^-, and PO_4^{3-}) were converted to sub-index scores (qi) by linear interpolation between breakpoints based on QCVN 08-MT:2023/BTNMT (level B) [8] and international aquaculture standards [9,10].

$$AWSI = \frac{\sum q_i w_i}{\sum w_i}$$

where w_i is the weight assigned to parameter i. Higher weights were assigned to DO(4) and to pH NH_4^+ and NO_2^- (3 each). AWSI was calculated when at least four valid values were available and classified as Excellent (≥91), Good (76–90), Fair (51–75), Poor (26–50), or Very Poor (<26).

3. Results

3.1. Descriptive Statistics

Tables 1 and 2 summarise overall and seasonal statistics for the twelve parameters. DO decreased from upstream to downstream, from 6.60 ± 0.83 mg/L at Tan Chau to 5.74 ± 0.98 mg/L at Can Tho, indicating stronger downstream organic pressure. pH was highest at Tan Chau (7.37 ± 0.33) and lowest at My Thuan (7.07 ± 0.34).

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Table 1. Overall statistics (mean ± SD) of twelve water quality parameters at four monitoring stations (2013–2024).

Parameter	Tan Chau	Chau Doc	My Thuan	Can Tho
DO (mg/L)	6.60 ± 0.83	6.18 ± 0.93	6.06 ± 0.84	5.74 ± 0.98
BOD_5 (mg/L)	2.62 ± 0.85	2.74 ± 0.83	2.58 ± 0.83	2.62 ± 0.89
TSS (mg/L)	31.5 ± 40.6	27.8 ± 31.9	25.8 ± 31.0	23.1 ± 24.4
PO_4^{3-}(mg/L)	0.034 ± 0.185	0.035 ± 0.152	0.031 ± 0.159	0.042 ± 0.155
NO_2^- (mg/L)	0.017 ± 0.031	0.027 ± 0.038	0.025 ± 0.037	0.021 ± 0.034
NO_3^- (mg/L)	0.30 ± 0.95	0.31 ± 0.90	0.24 ± 0.20	0.36 ± 0.45
NH_4^+ (mg/L)	0.14 ± 0.26	0.16 ± 0.23	0.13 ± 0.18	0.13 ± 0.19
Temperature (°C)	27.3 ± 1.8	27.4 ± 1.9	27.2 ± 1.5	27.4 ± 1.8
pH	7.37 ± 0.33	7.18 ± 0.25	7.07 ± 0.34	7.12 ± 0.23
EC (µS/cm)	176.5 ± 65.4	173.5 ± 62.8	178.5 ± 63.2	169.4 ± 58.8
COD (mg/L)	9.6 ± 3.7	10.1 ± 4.7	9.0 ± 3.4	9.1 ± 3.6
Cl^- (mg/L)	13.9 ± 9.9	13.7 ± 9.0	14.0 ± 9.6	13.4 ± 8.9

Table 2. Seasonal statistics (mean ± SD) of twelve water quality parameters at four monitoring stations (dry: December–May; rainy: June–November).

Parameter	Tan Chau		Chau Doc		My Thuan		Can Tho	
	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy
DO (mg/L)	6.69 ± 0.91	6.52 ± 0.74	6.11 ± 0.94	6.25 ± 0.91	6.03 ± 0.89	6.10 ± 0.79	5.67 ± 1.03	5.82 ± 0.92
BOD_5 (mg/L)	2.57 ± 0.88	2.67 ± 0.83	2.57 ± 0.75	2.90 ± 0.87	2.52 ± 0.89	2.63 ± 0.77	2.61 ± 0.85	2.63 ± 0.94
TSS (mg/L)	10.5 ± 5.6	52.5 ± 48.8	12.6 ± 8.0	43.0 ± 39.0	13.7 ± 9.5	36.0 ± 38.4	13.9 ± 7.3	31.7 ± 30.9
PO_4^{3-} (mg/L)	0.053 ± 0.261	0.015 ± 0.020	0.053 ± 0.213	0.016 ± 0.012	0.048 ± 0.232	0.016 ± 0.018	0.066 ± 0.222	0.020 ± 0.016
NO_2^- (mg/L)	0.021 ± 0.039	0.013 ± 0.020	0.037 ± 0.048	0.018 ± 0.021	0.032 ± 0.047	0.019 ± 0.026	0.020 ± 0.028	0.022 ± 0.040
NO_3^- (mg/L)	0.34 ± 1.31	0.26 ± 0.22	0.35 ± 1.24	0.27 ± 0.22	0.22 ± 0.20	0.27 ± 0.20	0.40 ± 0.59	0.32 ± 0.25
NH_4^+ (mg/L)	0.20 ± 0.34	0.08 ± 0.09	0.20 ± 0.27	0.12 ± 0.16	0.17 ± 0.24	0.11 ± 0.11	0.17 ± 0.24	0.10 ± 0.11
Temp (°C)	27.1 ± 1.8	27.5 ± 1.7	27.2 ± 2.1	27.5 ± 1.8	27.0 ± 1.6	27.3 ± 1.5	27.3 ± 1.9	27.4 ± 1.8
pH	7.49 ± 0.29	7.26 ± 0.32	7.22 ± 0.23	7.13 ± 0.27	7.11 ± 0.33	7.05 ± 0.34	7.14 ± 0.20	7.10 ± 0.26
EC (µS/cm)	214.2 ± 58.1	138.7 ± 48.4	198.6 ± 61.1	148.4 ± 54.1	210.5 ± 62.8	151.0 ± 49.4	196.1 ± 49.8	144.5 ± 55.8
COD (mg/L)	9.5 ± 4.1	9.7 ± 3.3	9.6 ± 5.5	10.5 ± 3.6	8.8 ± 3.4	9.1 ± 3.5	9.1 ± 3.9	9.0 ± 3.3
Cl^- (mg/L)	16.0 ± 11.4	11.8 ± 7.6	14.1 ± 7.7	13.3 ± 10.2	15.8 ± 11.3	12.4 ± 7.5	15.0 ± 8.8	11.9 ± 8.7

TSS was higher in the rainy season (32.67–52.52 mg/L) than in the dry season (10.46–13.91 mg/L) at all stations (Mann-Whitney $\rho < 0.001$, Figure 2a), reflecting flood-driven sediment mobilisation. NH_4^+ and PO_4^{3-} tended to increase in the dry season, likely because of reduced dilution, with much higher dry-season variability (CV up to 490%, Figure 2b) (Figure 2). EC, Cl^- were also higher in the dry season.

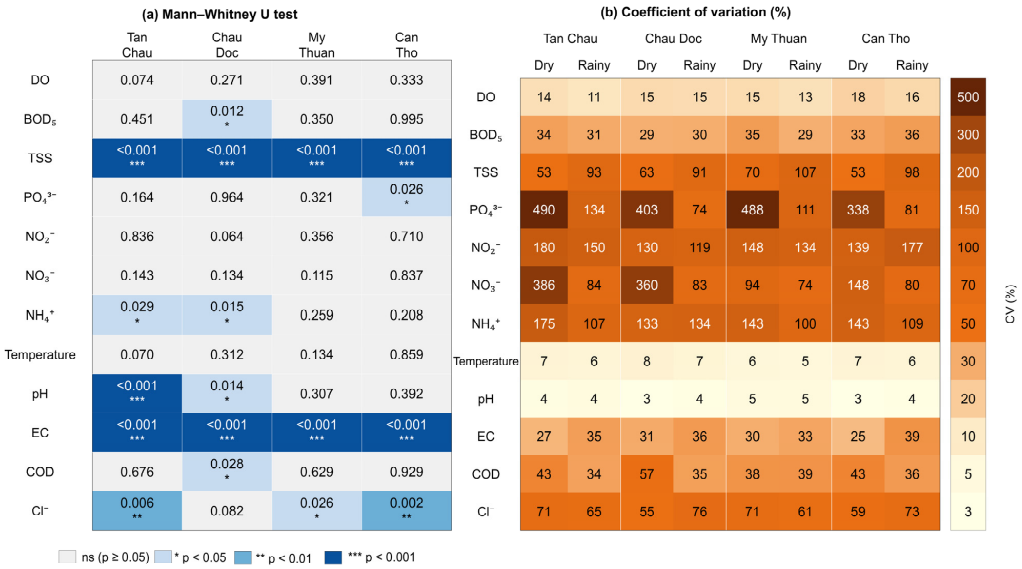


Figure 2. Seasonal variability of water quality parameters across four monitoring stations and two seasons (dry: December–May; rainy: June–November). (**a**) $\rho - values$ of the two-sided Mann-Whitney U test between seasons; (**b**) coefficient of variation (CV,%) by station and season (logarithmic colour scale). Shading in (**a**) ns = no significant. $\rho > 0.05$; * $\rho < 0.05$; ** $\rho < 0.01$, *** $\rho < 0.001$).

3.2. Spatial Variation: Kruskal–Wallis Test

Table 3 shows the Kruskal–Wallis results. Significant spatial differences were detected for DO ($H = 62.19, p < 0.001$), pH ($H = 72.06, p < 0.001$), PO_4^{3-} ($H = 35.02, p < 0.001$), NO_3^- ($H = 11.72, p = 0.008$), and NO_2^- ($H = 9.40, p = 0.024$). BOD_5, TSS, NH_4^+, temperature, EC, COD, and Cl^- were not significantly different among stations.

Table 3. Results of the Kruskal–Wallis test for twelve water quality parameters across four monitoring stations (df = 3 for all parameters).

Parameter	H Statistic	*p*-Value	Sig.	df	Interpretation
DO	62.192	<0.001	***	3	Significant
BOD_5	2.743	0.433	ns	3	Not significant
TSS	0.727	0.867	ns	3	Not significant
PO_4^{3-}	35.024	<0.001	***	3	Significant
NO_2^-	9.403	0.024	*	3	Significant
NO_3^-	11.723	0.008	**	3	Significant
NH_4^+	5.468	0.141	ns	3	Not significant
Temperature	0.464	0.927	ns	3	Not significant
pH	72.059	<0.001	***	3	Significant
EC	1.237	0.744	ns	3	Not significant
COD	5.731	0.125	ns	3	Not significant
Cl^-	0.238	0.971	ns	3	Not significant

Note: H = Kruskal—Wallis test statistic; df = degrees of freedom; ns = not significant ($(\rho > 0.05$; * $\rho < 0.05$; ** $\rho < 0.01$, *** $\rho < 0.001$).

3.3. Post Hoc Pairwise Comparisons: Dunn's Test

Figure 3 presents Dunn's test for the five significant parameters with significant Kruskal—Wallis results. DO at Tan Chau differed significantly from all other stations

($\rho < 0.001$) (Chau Doc, My Thuan and Can Tho ($p < 0.001$), confirming declining oxygen availability downstream. Tan Chau also showed significantly higher pH than the other stations. Can Tho had significantly higher PO_4^{3-} than upstream sites ($p < 0.012$), and Tan Chau also differed from Chau Doc ($p < 0.025$), My Thuan ($p < 0.045$). NO_3^- differed only between Can Tho and Tan Chau ($p < 0.011$) and Chau Doc ($p < 0.033$) (and NO_2^- only between Tan Chau and Chau Doc ($p < 0.041$).

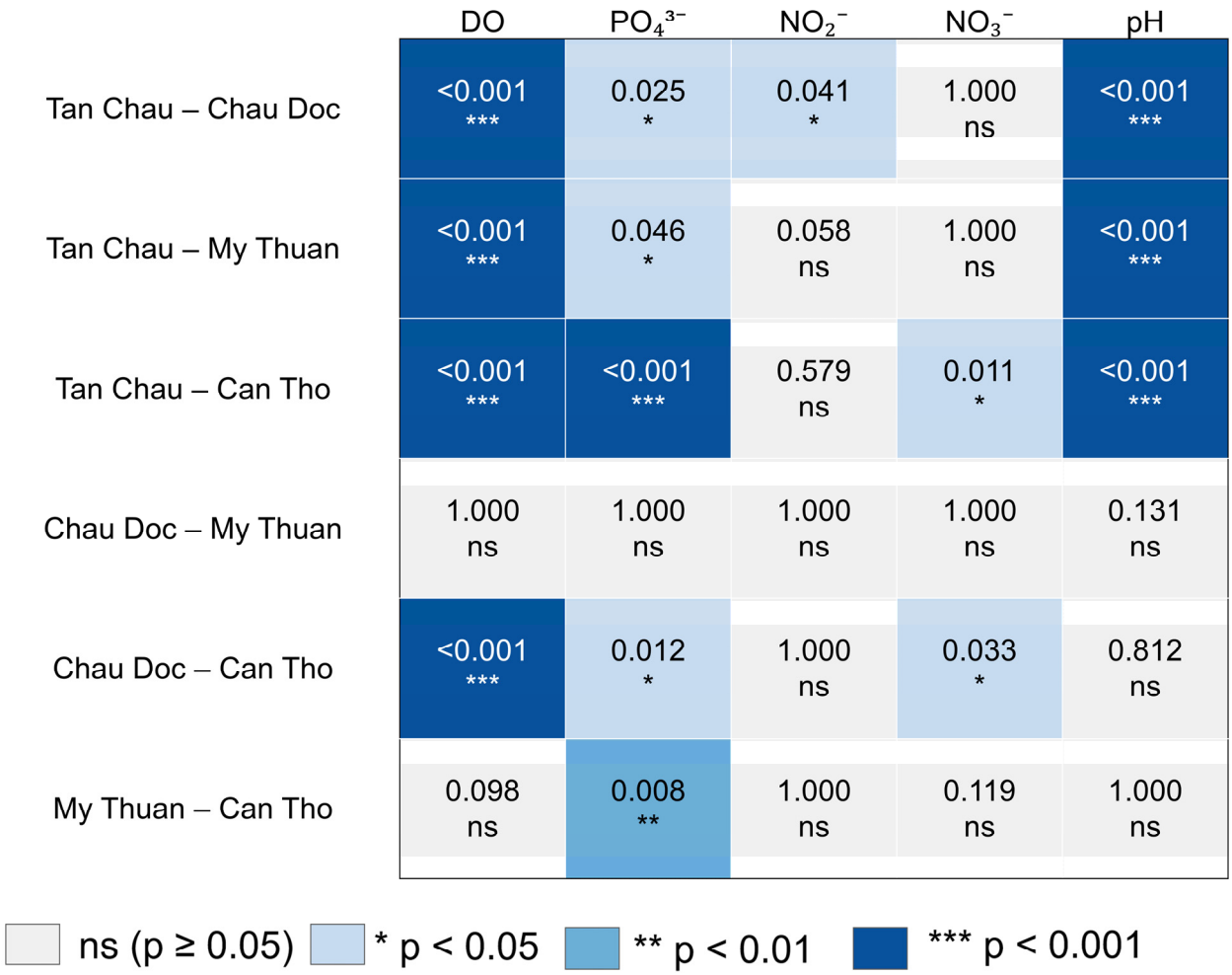


Figure 3. Dunn's post hoc test heatmap showing pairwise comparisons between monitoring stations. Shaded cells indicate statistically significant differences ($p < 0.05$, Bonferroni-corrected). *ns = not significant* (($\rho > 0.05$; * $\rho < 0.05$; ** $\rho < 0.01$, *** $\rho < 0.001$).

3.4. Source Apportionment: Principal Component Analysis

PCA retained four components with eigenvalues > 1 (2.89, 1.73, 1.43 and 1.22), 60.5% of total variance (Figure 4a). PC1 (24.1%) had strong positive loadings for temperature, Cl^- (0.83), negative DO (−0.64), with moderate loadings EC (0.56), NO_3^- (0.55) reflecting dry-season low-flow conditions with higher temperature and ion concentration, lower oxygen (Figure 4b). PC2 (14.3%) contrasted EC (0.70) with TSS (−0.67), representing flood-pulse dilution and sediment input (Figure 4c). The PCA score plot showed only a weak upstream-downstream separation, with Tan Chau associated more higher DO (Figure 4b).

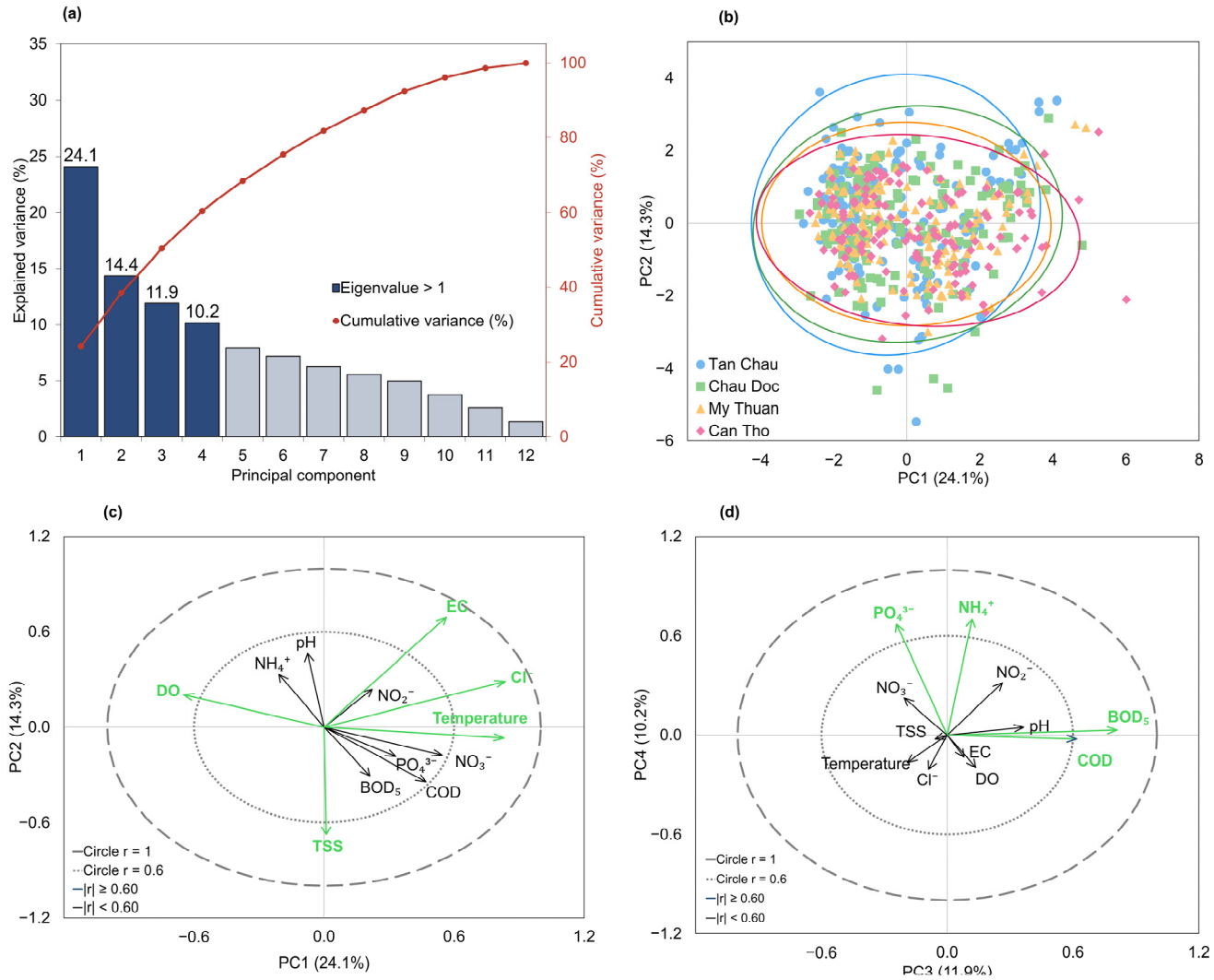


Figure 4. PCA results: (**a**) scree plot showing the percentage of variance explained by each principal component dark bars: eigenvalue > 1 and cumulative variance (line); (**b**) PCA biplot (PC1 vs. PC2) with 95% confiden ellipses for each station; (**c**) loadings correlations between parameters and components ong PC1–PC2; (**d**) loadings ong PC3 and PC4. Dark circles mark $|r| = 1$ and dotted circles $|r| = 0.6$ with $|r| \geq 0.6$ are shown in bold.

PC3 (11.9%) was associated with BOD_5 (0.81) and COD (0.62), indicating organic enrichment, whereas PC4 (10.2%) was linked to NH_4^+ (0.69) PO_4^{3-} (0.68) (Figure 4c). PC4 was driven largely by a few early—2013 samples with exceptionally high concentrations and should be interpreted with caution. Station score distributions overlapped strongly (Figure 4b), with only a slight shift along PC1 from Tan Chau (mean −0.28) to Can Tho (0.28).

3.5. Aquaculture Water Suitability Assessment (AWSI)

AWSI scores for all station–season combinations fell within the Good to Excellent classes (Table 4; Figure 5) and differed significantly among stations (Kruskal—Wallis $\rho < 0.01$). Most samples were classified as Good or Excellent; only 2–4% of samples per station were Fair, and none fell below the Fair class. The highest score was recorded at Tan Chau in the dry season (91.6 ± 5.8, Excellent), whereas the lowest occurred at Chau Doc in the rainy season (86.7 ± 5.6, Good). Dry season AWSI values were consistently higher than rainy-season values at all stations. Rainy-season scores were lowered mainly by high TSS,

whereas dry-season scores were reduced by higher NH_4^+, NO_2^- at Can Tho by lower DO. COD sub-indices were moderate in both seasons.

Table 4. Aquaculture Water Suitability Index (AWSI) scores by station and season, with suitability classification and management implications.

Station	Season	AWSI (Mean ± SD)	Class	Aquaculture Suitability Assessment
Tan Chau	Dry	91.6 ± 5.8	Excellent	Suitable for catfish (*P. hypophthal-mus*)
Tan Chau	Rainy	88.9± 5.2	Good	Suitable for catfish TSS elevated
Chau Doc	Dry	88.1 ± 6.4	Good	Acceptable for catfish, monitor COD & NO_2^-
Chau Doc	Rainy	86.7 ± 5.6	Good	Acceptable for catfish, monitor COD & pH
My Thuan	Dry	88.4 ± 5.0	Good	Acceptable for catfish, monitor COD & pH
My Thuan	Rainy	87.5 ± 5.0	Good	Acceptable for catfish, TSS elevated
Can Tho	Dry	87.5 ± 5.0	Good	Acceptable for catfish, monitor DO
Can Tho	Rainy	87.4 ± 6.3	Good	Acceptable for catfish, TSS elevated

Note: AWSI classification—Excellent (≥91), Good (76–90), Fair (51–75), Poor (26–50), Very Poor (<26). Thresholds based on QCVN 08:2023/BTNMT (Level B) [8] and Boyd (2000) [10].

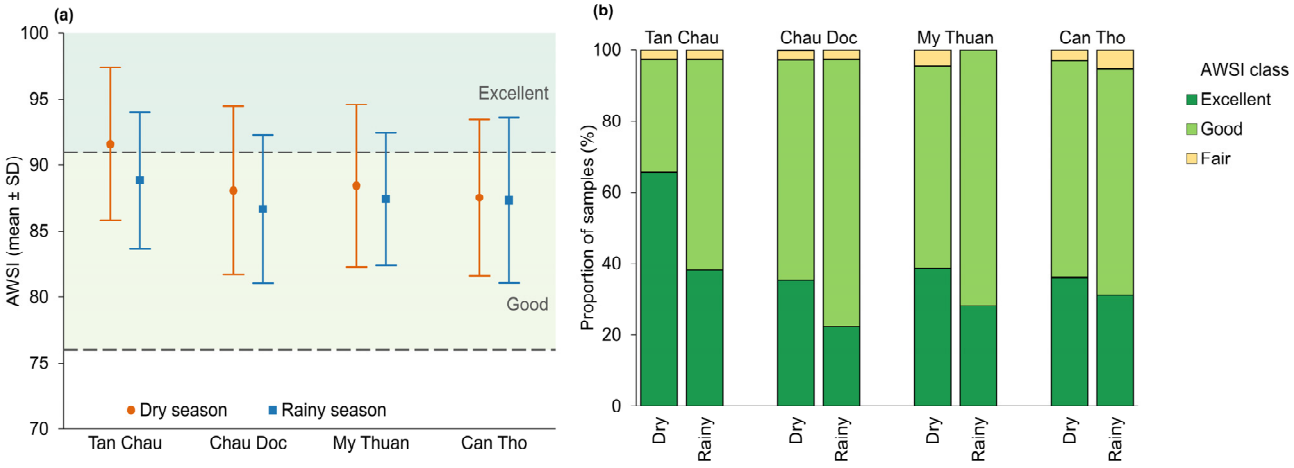


Figure 5. Seasonal AWSI scores at four monitoring stations (2013–2024). (**a**) mean AWSI; error bars represent ± 1 standard deviation; horizontal dashed lines indicate class boundaries (76 = Good; 91 = Excellent); (**b**) proportion of samples in each AWSI data.

4. Discussion

4.1. Spatial Patterns and Drivers of Water Quality Degradation

The upstream-to-downstream decline in DO and pH is consistent with increasing organic pressure along the river system [12]. Although annual mean DO remained above 4 mg/L at all stations, minimum values at Can Tho dropped to 3.0 mg/L, indicating short-term stress that may affect cultured species [9,10].

The lack of significant spatial differences in BOD_5, TSS, NH_4^+, temperature, EC, and COD may reflect strong hydrological connectivity and diffuse inputs across the delta [13].

In contrast, elevated $PO_4^{3}-$ at Can Tho is consistent with stronger urban and domestic inputs in the lower delta [6].

4.2. Seasonal Dynamics and Tidal Influences

Higher rainy-season TSS confirms the importance of the Mekong flood pulse for sediment transport [14]. Dry-season increases in NH_4^+ and PO_4^{3-} indicate lower dilution capacity and greater eutrophication risk when river water is used for aquaculture supply.

4.3. PCA Source Attribution

The PCA results indicate that seasonal hydrology is the dominant source of water-quality variation in the Tien–Hau system: PC1 and PC2 together (38.4%) describe dry-season low-flow conditions and flood-pulse dilution [15]. Organic enrichment (PC3, 11.9%) explains a smaller share but is consistent with previous studies identifying aquaculture effluent, wastewater and agricultural residues as important pressures in the Mekong Delta [5,7,16].

Becauce Cl^- and EC did not differ among stations (Table 3) but were higher in the dry season (Figure 2), their association with PC1 more likely reflects ionic concentration under low discharge than direct seawater intrusion at the land stations. Nevertheless, reduced dry-season discharge coincides with high water demand and remains an important constraint for aquaculture water supply in downstream areas [14,17].

4.4. Aquaculture Suitability: Station–Season–Species Recommendations

AWSI converts the multi-parameter dataset into practical guidance for aquaculture management [18]. The main station–season implications are summarised below.

Tan Chau, dry season (AWSI: Excellent, 91.6): Most favourable conditions in the dataset and suitable for pangasius culture (*Pangasianodon hypophthalmus*) with minimal pre-treatment requirements [16].

Tan Chau, rainy season (AWSI: Good, 88.9): Suitable for pangasius, but elevated TSS requires setting before water intake. Chau Doc and My Thuan, both seasons (AWSI: Good, 86.7-88.4): Generally acceptable for catfish with routine management, but less suitable for black tiger shrimp (*Penaeus monodon*) because of stricter DO, pH, NH_4^+, and NO_2^- requirements [9].

Can Tho, dry season (AWSI: Good, 87.5): lowest DO in the dataset. Direct intake should be avoided during low-flow periods unless pre-treatment such as settling, filtration, or aeration is applied [8,9].

4.5. Regulatory Compliance and Management Implications

Most annual mean values complied with QCVN 08:2023/BTNMT level B [8], but intermittent exceedances were still important for production risk. In the dry season, DO fell below 5 mg/L at Can Tho and NH_4^+ exceeded 0.5 mg/L at Chau Doc and Can Tho during some observations, indicating potential constraints during stocking and early grow-out.

These findings support season-specific timing of water abstraction and stronger dry-season buffering measures, especially at downstream stations [18].

5. Conclusions

This study provides a long-term assessment of Tien–Hau river surface water quality for aquaculture suitability during 2013–2024. Significant spatial gradients were found for DO, pH, PO_4^{3-}, and inorganic nitrogen, with Tan Chau generally showing the best water quality. PCA identified four main drivers of variation: organic enrichment, hydrological dynamics, nutrient runoff, and salinity intrusion, while AWSI highlighted staion-season

differnces, with dry-season Tan Chau as the most suitable and rainy-season Chau Doc as the least suitable.

Overall, the results indicate that aquaculture water intake should be seasonally adjusted: upstream dry-season water is the most favourable, whereas rainy-season water requires closer quality control and, in some cases, pre-treatment before use.

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

Abbreviations

The following abbreviations are used in this manuscript:

AWSI	Aquaculture Water Suitability Index
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EC	Electrical Conductivity
PCA	Principal Component Analysis
QCVN	Quy Chuẩn Kỹ thuật Quốc gia (Vietnamese National Technical Regulation)
TSS	Total Suspended Solids

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