Variation of Water Quality in Intensive Aquaculture Areas of the Mekong Delta, Vietnam

TRAN VAN VIET, AU VAN HOA, HUYNH TRUONG GIANG, VU NGOC UT*
College of Aquaculture and Fisheries, Can Tho University, Can Tho, Viet Nam

*E-mail: vnut@ctu.edu.vn |Received: 30/08/2022; Accepted: 22/06/2023

E-ISSN: 2073-3720
https://doi.org/10.33997/j.afs.2023.36.2.005

Abstract

The Mekong Delta produces about 70 % of Vietnam's national aquaculture output, and water quality management is a key factor in maintaining high levels of production and profitability. Effective water management strategies depend on understanding the spatial and temporal variations in water quality along major waterways. Therefore, this study aimed to assess the spatial and temporal fluctuation of water quality in the waterways of five provinces with intensive aquaculture operations in the Mekong Delta. The study sites included two inland provinces (An Giang and Can Tho) where striped catfish, *Pangasianodon hypophthalmus* (Sauvage, 1878), is farmed, and three coastal provinces (Soc Trang, Bac Lieu, and Ca Mau) where white leg shrimp, *Litopenaeus vannamei* (Boone, 1931), and black tiger shrimp *Penaeus monodon* Fabricius, 1798, are cultured. At each sampling site, physicochemical parameters were monitored for 12 months on the main rivers which supply water to aquaculture systems. Water quality data were analysed and compared based on the coefficient of variation (CV), Pearson correlation coefficients to identify relationships among variables and principal component analysis (PCA) to identify 2–3 key parameters having the most significant influence on spatial and temporal variation in water quality in each province. BOD, COD, PO_4^{3-}, S^{2-}, NO_2^- and NO_3^- were highly variable (CV 40–120 %). Significant interrelationships ranged from -0.5 to 0.5 between many water quality parameters. Overall, water in most provinces was considered polluted. However, the water quality parameters, except for S^{2-} and NO_2^-, were within acceptable levels specified by National Technical Regulation on Surface Water Quality for Protection of Aquatic Life.

Keywords: black tiger shrimp, brackish water aquaculture, inland aquaculture, striped catfish, white leg shrimp

Introduction

The Mekong Delta covers an area of nearly 40,000 km^2 of low (<2 m above msl), flat land in the south of Vietnam. The area is dissected by a network of rivers, canals and other waterways, and this access to water and its topography make it ideal for agriculture and aquaculture (FAO, 2019). Aquaculture currently accounts for nearly 70 % of the total national aquaculture output and contributes over 3.5 % to the gross domestic product (GDP) (General statistical office of Vietnam-GSO, 2020). The main aquaculture species are striped catfish *Pangasianodon hypophthalmus* (Sauvage, 1878) in freshwater areas, white leg shrimp, *Litopenaeus vannamei* (Boone, 1931), and black tiger shrimp, *Penaeus monodon* Fabricius, 1798, in brackish water areas, all of which are cultured intensively or super-intensively on a large scale (Silva and Phuong, 2011). The culture area for striped catfish was 6,600 ha in 2019 (MARD, 2019), The total production rose from 1.1 million tonnes in 2015 to 1.6 million tonnes in 2019 (VASEP, 2021), while in 2018, the total area for shrimp was around 720,000 ha and production was about 745,000 tonnes (FAO, 2019).

Water quality is important in determining the quantity and quality of aquaculture products (Boyd and Tucker, 1998; Boyd, 2003). Parameters such as pH, salinity, dissolved oxygen (DO), biological oxygen demand (BOD), nitrite (NO_2^-), sulphide (S^{2-}), phosphate (PO_4^{3-}), total coliforms, and others can all affect the health, survival and growth of cultured fish and shrimp (Svobodova et al., 1993). In an aquaculture pond complex and dynamic environment, water quality parameters are influenced by internal and external factors (Wilbers et al., 2014). A rapid and dramatic change in one or more of these parameters could lead to the deterioration of water quality (Boyd, 2003) with adverse effects on the health, growth, and yield of the cultured species.

Given the complexity of interconnections between waterways in the Mekong Delta, water quality for aquaculture showed temporal and spatial variations, influenced by factors such as freshwater flow from upstream in the Mekong River and saltwater fluxes driven by tides from the sea. Furthermore, the water quality is also influenced by the proximity to domestic, industrial, agricultural and aquacultural wastewater sources and seasonal rainfall patterns. This study used multivariate statistical techniques to examine the spatial and temporal variation in water quality in the Mekong Delta aquaculture areas and identify the key factors responsible for this variation.

Materials and Methods

Study area

The study was conducted in five of the 13 provinces in the Mekong Delta, specifically in An Giang (AG) and Can Tho (CT), freshwater areas with high-intensity striped catfish, *P. hypophthalmus* cultivation. The Department of Agriculture and Rural Development of An Giang (DARD of AG), reported a significant increase in the culture of striped catfish. The area of culture increased from 550 ha in 2019 to 1,390 ha in 2021, resulting in production of 273,939 tonnes and 454,000 tonnes, respectively. Soc Trang (ST), Bac Lieu (BL) and Ca Mau (CM) (Fig. 1), are brackish water areas with white leg shrimp as the main culture species. About 10–15 % of the area in each province is used for intensive shrimp culture operating closed water system. While the remaining areas, the stocking density is low where the farming is on an extensive scale on a rotation system in rice fields or an integrated shrimp-mangrove farming system. According to GSO (2023), the Mekong Delta's total area of coastal shrimp in 2021 was 811,600 ha, in which ST accounted for 72,400 ha, BL 144,500 ha and CM 287,000 ha. Total shrimp production in 2021 was 836,286 tonnes, in which ST, BL and CM produced 167,711 tonnes, 154,826 tonnes, and 205,300 tonnes, respectively.

Most striped catfish and brackish water shrimp production are from intensive culture systems. In AG and CT, the typical practice during water exchange is to discharge water from ponds into the river. This is done through a designated area covered with water hyacinth, *Eichhornia crassipes* (Mart.), spanning approximately 6–10 m in length, to reduce the amount of nutrients released into the river. In most cases of intensive shrimp farms, a circulating water treatment system is employed in which water in the pond is filtered through a filter tank inside the pond to reduce the suspended solids. Other sources of pollutants include liquid wastes from industrial zones, which are treated before discharge to comply with regulations by the Vietnamese government, and wastes from wet markets and human activities, which are not subject to strict government regulations, as they are thought to be a minor contributor to poor water quality.

Data collection

Nine sampling sites were selected along the main rivers in each of the five provinces, the Hau River (for AG and CT), the My Thanh River (for ST) and the Ganh Hao River (for BL and CM). These three rivers are the five provinces' main water supply for aquaculture activities. Sampling sites are designated by red dots in Figure 1.

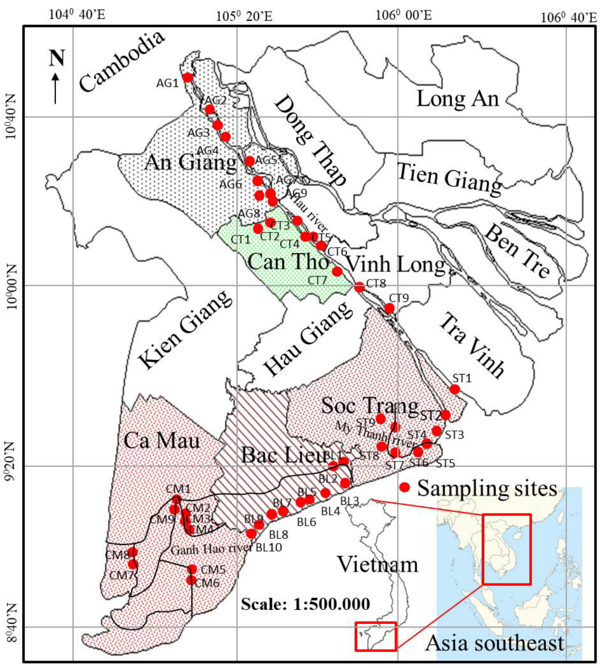

Fig. 1. Sites (red dots) for water parameters sampling along the river in An Giang (AG), Can Tho (CT), Soc Trang (ST) and the coasts in ST, Bac Lieu (BL) and Ca Mau (CM) provinces of the Mekong Delta for water quality mapping.

Sampling was conducted monthly at a depth of 20–30 cm from the surface at all sites from January to December 2019, and 9 stations for each province (12 times × 9 points = 108). Water temperature (Temp.), pH, salinity (Sal.) and dissolved oxygen (DO) were measured *in situ* with a Hanna HI 9828 Multi-parameter (Table 1). For chemical and biological parameters, water samples were collected in 1 L - plastic bottles and kept in the dark in an ice chest during transport to the laboratory at Can Tho University, where they were stored at 4 °C until analysed. Alkalinity (Alk.), BOD, chemical oxygen

Table 1. Water quality parameters and analytical methods.

No.	Parameters	Methods
1	Temperature, pH, salinity, DO	Directly measured on-site using Hanna multi-parameter meter (Model: HI 9828, UK)
2	BOD	5210 B. 5 - day BOD test (APHA, 2017)
3	COD	5220 C. Closed reflux, titrimetric method (APHA, 2017)
4	Alkalinity	2320 B. Titration method (APHA, 2017)
5	TAN	4500 - NH_3 - F. Phenate method (APHA, 2017)
6	NO_2^- - N	4500 - NO_2^- B. Colorimetric method (APHA, 2017)
7	NO_3^- - N	4500 - NO_3^- - B. Salicylate method (Monterio et al., 2003)
8	TSS	2540 D. Total suspended solids dried at 103-105 °C (APHA, 2017)
9	S^{2-}	4500 - PO_4^{3-} - D. Stannous chloride method (APHA, 2017)
10	PO_4^{3-} - P	4500 - PO_4^{3-} - D. Stannous chloride method (APHA, 2017)
11	Coliform and *E. coli*	9221 C. Estimation of bacterial density (APHA, 2017)

DO: Dissolved oxygen; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^--N: Nitrite; NO_3^--N: Nitrate; PO_4^{3-}: Phosphate; TSS: Total suspended solids; S^{2-}: Sulphide.

demand (COD), total suspended solids (TSS), total ammonia nitrogen (TAN), nitrite (NO_2^--N), nitrate (NO_3^--N), phosphate (PO_4^{3-}), sulphide (S^{2-}), total coliforms (Col.) and *Escherichia coli* were analysed in the laboratory following the procedures of standard methods (APHA, 2017) (Table 1).

Data analysis

Monthly values for each parameter at each sampling site were summarised using summary statistics such as mean and standard deviation. To assess the differences in parameter means between sampling sites were compared using one-way ANOVA followed by post hoc Tukey's tests to identify significant differences. The variability of water quality parameters at each site was assessed using coefficient of variation (CV %) (Fowler and Cohen, 1992), and to determine significant correlations between different water quality parameters, the Pearson Correlation Coefficient (r) was used (Khatoon et al., 2013; Abdelrahman et al., 2018). Finally, principal component analysis (PCA) was used to reduce the 11 original water quality parameters into smaller key variables (3–4 PCs). The first four PCs, which accounted for over 50 % of the results, identify the main water quality parameters responsible for variation in water quality within each province. For PCA, all data were normalised before analysis. The analysis was confined to the first four principal components (PCs), including PC1 (representing for BOD, COD and PO_4^{3-}), PC2 (DO and alkalinity), PC3 (temperature and NO_3^-) and PC4 (pH and NO_2^-). All statistical analyses were carried out with R software, version 4.1.0 (https://www.r-project.org).

PCA was applied for spatial data analysis to extrapolate data as a dimensional reduction method by transforming a large set of variables into smaller ones while preserving most of the information from the large dataset (Jolliffe and Cadima, 2016). PCA has the advantage of retaining the original information and identifying uncorrelated variables simultaneously, aiming to screen out the independent principal component factors through dimension reduction analysis (Shine, 1995; Loska, 2003; Simeonov et al., 2003).

Results

Variation of water parameters (CV %)

Spatial and temporal variations of physicochemical parameters were observed between the sampling sites (Table 2). Temperature and pH remained stable throughout the study. Salinity had a high variation at all sampling sites in the 3 coastal provinces, with a CV in the range 41–73 % (Table 3 and Fig. 2), with low salinity (0–3.6 $mg.L^{-1}$) on the My Thanh River in Soc Trang, which is about 20 km upstream from the estuary. In addition, the other parameters, such as NO_2^-, S^{2-}, TAN, and TSS fluctuated greatly at sampling sites (Table 3 and Fig. 2). The CV in both Coliforms and *E. coli* varied from 155 to 322 %.

Pearson correlation coefficient (r)

Correlation coefficients (r) ranged from 0.5 to 0.8 for pH and temperature in BL, and for *E. coli* and Coliforms in AG, BL and CM, but most other variables were poorly correlated (Tables 4, 5, 6, 7 and 8).

Principal component analysis (PCA)

PCA results for the first four principal components had very low values in all five provinces (Table 9 and Fig. 3 for AG and CT; Table 10 and Fig. 4 for ST, BL and CM), indicating that a small number of key parameters did not dominate temporal and spatial variability in water quality. PCA showed that the first 4 PCs played

Table 2. Mean values and standard deviation of physicochemical variables at the sampling sites in five provinces in the Mekong Delta and the last two columns are National Technical Regulation recommendations for Surface Water Quality for Protection of Aquatic Life.

No.	Variables	AG (n = 108)	CT (n = 108)	ST (n = 108)	BL (n = 108)	CM (n = 108)	QCVN 38: 2011/BTNMT	QCVN 08: 2015/BTNMT
1	Temp. (°C)	30.6 ± 1.3^{ac}	30.3 ± 3.0^{abc}	29.8 ± 1.3^{bd}	30.2 ± 1.6^{abc}	30.3 ± 1.3^{abc}		
2	pH	7.3 ± 0.3^{a}	7.3 ± 0.3^{ab}	7.7 ± 0.3^{de}	7.9 ± 0.3^{b}	7.8 ± 0.2^{e}	6.5-8.5	6.0-8.5
3	Sal. (mg.L^{-1})			7.3 ± 3.8^{a}	15.4 ± 6.2^{b}	14.5 ± 7.3b^{c}		
4	DO (mg.L^{-1})	5.1 ± 0.8^{a}	4.4 ± 0.7^{b}	4.1 ± 1.0^{d}	4.5 ± 0.8^{b}	4.4 ± 0.7^{b}	≥ 4	≥ 6
5	BOD (mg.L$_{-1}$)	2.9 ± 0.8^{a}	4.0 ± 1.0^{c}	4.2 ± 1.3^{c}	3.8 ± 1.0^{b}	3.7 ± 1.0^{b}		≥ 4
6	COD (mg.L^{-1})	6.2 ± 2.4^{a}	5.1 ± 1.6^{b}	6.6 ± 2.7^{a}	7.4 ± 3.1^{a}	5.5 ± 3.4^{b}		10
7	Alkalinity (mg.L^{-1})	64.0 ± 15.9^{a}	64.2 ± 14.1^{a}	89.6 ± 21.2^{bc}	129.4 ± 34.5^{be}	131.1 ± 29.6^{be}		
8	TAN (mg.L^{-1})	0.4 ± 0.5^{ab}	0.3 ± 0.5^{ac}	0.2 ± 0.3^{bc}	0.4 ± 0.5^{ab}	0.2 ± 0.2^{bc}	1	0.3
9	NO_2^- (mg.L^{-1})	0.1 ± 0.1^{a}	0.2 ± 0.3^{b}	0.1 ± 0.1^{a}	0.1 ± 0.3^{a}	0.2 ± 0.2^{b}	0.02	0.05
10	NO_3^- (mg.L^{-1})	0.3 ± 0.3^{a}	0.2 ± 0.1^{c}	0.3 ± 0.2^{a}	0.6 ± 0.4^{b}	0.6 ± 0.4^{b}	5	2
11	PO_4^{3-} (mg.L^{-1})	0.2 ± 0.2^{a}	0.2 ± 0.2^{a}	0.4 ± 0.4^{b}	0.2 ± 0.2^{a}	0.2 ± 0.1^{a}		0.1
12	TSS (mg.L^{-1})	45.2 ± 37.0^{a}	48.6 ± 37.7^{a}	240.5 ± 84.5^{c}	370.9 ± 303.8^{d}	317.8 ± 196.6^{e}	100	20
13	S^{2-} (mg.L^{-1})	0.01 ± 0.01^{a}	0.04 ± 0.02^{b}	0.09 ± 0.07^{c}	0.05 ± 0.05^{b}	0.04 ± 0.03^{b}		
14	Coliforms (MPN.100 mL^{-1})	56.4 ± 99.3^{a}	73.0 ± 124.8^{b}	89.7±86.9^{c}	89.1 ± 143.6^{c}	47.5 ± 93.4^{a}		2,500
15	*E. coli* (MPN.100 mL^{-1})	2.9 ± 4.4^{a}	2.8 ± 5.5^{a}	0.9 ± 1.2^{b}	3.0 ± 5.4^{a}	1.8 ± 3.3^{c}		20

Temp: Temperature; Sal.: Salinity; DO: Dissolved oxygen; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; PO_4^{3-}: Phosphate; TSS: Total suspended solids; S^{2-}: Sulphide. AG: An Giang, CT: Can Tho, ST: Soc Trang, BL: Bac Lieu and CM: Ca Mau.
National Technical Regulation on Surface Water Quality for Protection of Aquatic Life; QCVN 08-MT: 2015/BTNMT and QCVN 38: 2011/BTNMT: All values are presented as mean ± SD, and values with the same superscript letters on the same row indicate no significant difference ($P > 0.05$).

Table 3. Range of water quality variables (min-max) in five Mekong Delta provinces during the study period.

Variables	AG (n = 108)	CT (n = 108)	ST (n = 108)	BL (n = 108)	CM (n = 108)
Temp. (°C)	27.9-33.3	28.3-32.8	27.2-32.6	28.0-32.9	28.1-32.6
pH	6.7 -7.9	6.4-8.1	6.8-8.5	6.3-8.5	7.3-8.2
Salinity (ppt)	0	0	0.15-23.3	1.5-24.6	1.5-27.8
DO (mg.L^{-1})	3.0-6.8	3.0-5.9	2.2-7.1	2.8-6.4	3.0-6.2
TSS (mg.L^{-1})	5.0-260.0	7.9-199.0	31.6-812.0	34.0-1980.0	19.6-916.0
Alkalinity (mg.L^{-1})	34.1-93.0	33.0-85.0	32.0-177.0	34.5-264.7	69.0-195.0
BOD (mg.L^{-1})	1.2-5.1	2.2-6.2	1.2-7.2	1.0-7.6	2.0-5.9
COD (mg.L^{-1})	1.5-14.8	2.1-10.1	2.0-13.3	2.0-15.6	1.4-16.1
TAN (mg.L^{-1})	0.004-1.8345	0.005-2.584	0.005-1.9975	0.003-2.8905	0.005-1.406
NO_2^- (mg.L^{-1})	0.002-0.5445	0.005-0.005	0.0075-0.52	0.005-2.535	0.037-0.6405
NO_3^- (mg.L^{-1})	0.003-2.180	0.058-0.669	0.005-1.065	0.015-1.522	0.058-0.058
PO_4^{3-} (mg.L^{-1})	0.0045-0.935	0.005-0.837	0.017-3.057	0.006-1.439	0.007-0.6585
S^{2-} (mg.L^{-1})	0.0028-0.035	0.0065-0.095	0.006-0.2955	0.0031-0.545	0.003-0.1115
Coliforms (MPN.100 mL^{-1})	0.2-580.0	0.18-630.0	0.91-840	0.91-700	0.92-490
E. coli (MPN.100 mL^{-1})	0.018-24	0.01-26	0.018-31	0.016-34	0.024-25

Temp: Temperature; Sal: Salinity; DO: Dissolved oxygen; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; PO_4^{3-}: Phosphate; TSS: Total suspended solids; S^{2-}: Sulphide. AG: An Giang, CT: Can Tho, ST: Soc Trang, BL: Bac Lieu and CM: Ca Mau

Table 4. Pearson correlation coefficient (r) for the water quality variables in An Giang (AG) province in Mekong Delta during the study period.

Variables	Temp.	pH	DO	TSS	Alk.	BOD	COD	TAN	NO_2^-	NO_3^-	PO_4^{3-}	S^{2-}	Col.
pH	- 0.07												
DO	0.16	*0.47****											
TSS	- 0.17	0.002	- 0.16										
Alk.	*0.32****	- 0.02	0.28***	- 0.03									
BOD	- 0.29***	- 0.01	- 0.00	0.19	0.011								
COD	- 0.07	- 0.03	- 0.20*	0.20*	0.010	0.31							
TAN	- 0.09	*-0.47****	*- 0.41****	0.12	0.021	0.07	0.16						
NO_2^-	- 0.14	- 010	- 0.05	- 0.08	0.024***	0.01	- 0.04	0.29***					
NO_3^-	*0.37****	- 0.07	0.08	0.17	*0.42****	0.05	0.12	- 0.09	- 0.08				
PO_4^{3-}	- 0.20*	- 0.13	- 0.18	0.16	0.10	0.39***	*0.43****	- 0.27***	- 0.009	0.05			
S^{2-}	0.17	- 0.05	- 0.04	0.04	- 0.15	- 0.16	- 0.19	0.18*	0.11	- 0.03	- 0.02		
Col.	0.10	0.02	- 0.14	0.02	*- 0.40****	- 0.19	- 0.11	- 0.06	- 0.18	- 0.13	- 0.16	0.16	
E. coli	0.17	0.09	- 0.01	0.06	- 00.5	- 0.11	- 0.01	- 0.05	- 0.05	0.07	- 0.16	0.26***	*0.50****

Superscript: *** means that P < 0.01; and * means that $P < 0.05$.

Temp: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO^{2-}: Nitrite; NO^{3-}: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

Table 5. Pearson correlation coefficient (r) for the water quality variables in Can Tho (CT) city in Mekong Delta during the study.

Variables	Temp.	pH	DO	TSS	Alk.	BOD	COD	TAN	NO_2^-	NO_3^-	PO_4^{3-}	S^{2-}	Col.
pH	0.12												
DO	0.07	0.28***											
TSS	- 0.14	- 0.10	0.05										
Alk.	0.19*	- 0.01	0.23*	*- 0.35****									
BOD	0.02	0.12	*0.29****	- 0.12	0.07								
COD	0.07	- 0.09	0.03	0.21*	- 0.02	- 0.03							
TAN	- 0.15	- 0.18	- 0.25***	0.22*	- 0.09	*- 0.30****	0.08						
NO_2^-	0.08	- 0.26***	- 0.05	- 0.18	*0.46****	- 0.006	- 0.24***	0.13					
NO_3^-	- 0.10	- 0.05	- 0.03	- 0.11	0.15	- 0.04	- 0.29***	*- 0.29****	0.07				
PO_4^{3-}	- 0.14	- 0.09	- 0.21*	- 0.08	0.05	- 0.06	- 0.006	- 0.006	- 0.16	- 0.08			
S^{2-}	- 0.15	0.13	- 0.04	0.05	- 0.14	0.03	0.19	0.19*	- 0.20*	- 0.16	*0.36****		
Col.	0.26***	0.18	- 0.03	0.05	*- 0.51****	0.10	- 0.03	- 0.029	*- 0.32****	- 0.09	- 0.16	0.02	
E. coli	0.09	- 0.20	*- 0.31****	0.10	- 0.48***	- 0.05	- 0.08	- 0.08	- 0.21*	- 0.03	0.07	0.13	*0.37****

Superscript: *** means that P < 0.01; and * means that $P < 0.05$.

Temp: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO^{2-}: Nitrite; NO^{3-}: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

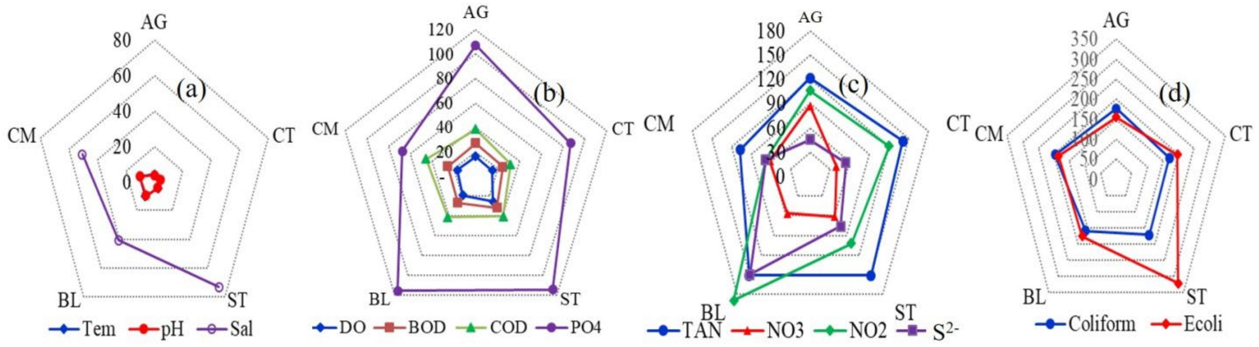

Fig. 2. Coefficient of variation (CV %) of physicochemical variables in five Mekong Delta provinces (An Giang: AG; Can Tho: CT; Soc Trang: ST; Bac Lieu: BL and Ca Mau: CM) during the study period. Tem.: Temperature; Sal.: Salinity; DO: Dissolved oxygen; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; S^{2-}: Sulphide.

a significantly explained surface water quality variation in AG province, accounting for 56.8 % of the total variation (Table 9). Furthermore, these variables were condensed into 2 new PCs in AG (Fig. 3). PC 1 was the most important significant factor contributing 17.9 % of the total variation. It represented physicochemical parameters such as PO_4^{3-}, BOD and COD (highlighted in the second column of Table 9), which are indicators of organic matter and eutrophication in the loading plot (Fig. 3). In terms of the spatial dimension in AG, the PC 1 was inversely correlated with the PC 2 and PC 3 for the physical parameters (Temp. and pH) and chemical parameters (Alk. and NO_3^-). Additionally, PC1 was associated with wastewater from animals and human activities, and f *E. coli* and coliform, respectively (Fig. 3).

In CT province, the first 4 PCs accounted for 54.6 % of the variance, with main contributions from variables such as Alk., S^{2-}, *E. coli*, pH, COD and Temp. (Table 9 and Fig. 3). PC 1, which explained 18.6 % of the variation, was influenced by S^{2-} and *E. coli*, displaying an inverse relationship with Alk. PC2 represented fluctuations caused by pH, while PC3 represented by COD accounted for 15.2 % and 11.8 % variance, respectively. The first 3 PCs collectively accounted for 45.6 % of the total variation. This created new physical PCs, indicating a positive correlation between pH and temperature but no significant correlation between Alk., NO_2^- and Coliform, *E. coli* and between pH and TAN regarding spatial dimension within CT (Fig. 3).

In coastal provinces, PCA results showed that the first 4 PCs explained 53.9 % of the total variation of water quality in ST (Table 10 and Fig. 4). PC 1, primarily associated with pH and DO accounted for 20.9 % of the variance. PC 2 explained 13.2 % and was significantly influenced by coliforms and PO_4^{3-}. PC 3, with a contribution mainly from TSS and S^{2-}, explained 10.8 % of the variation. Notably, the study found that both NO_2^- in June and S^{2-} in January, May and October exceeded the acceptable limits proposed by the National Technical Regulation (NTR).

In BL province, the first 4 PCs explained 58.7 % of the variance; PC 1 was significantly influenced by salinity and accounted for 20.9 % of the total variation. PC 2 influenced mainly by BOD explained 14.2 % of the variance, while PC 3 accounted for 12.1 % and was influenced mainly by Temp., Alk. and COD (Table 10).

In CM province, the first 4 PCs accounted for 56.9 % of the total variation in physicochemical parameters. PC 1, representing 19.9 % of the variance, was primarily associated with pH and NO_3^- (Table 10). PC 2 explained 15.5 % of the total variance with a high contribution from *E. coli*. PC 3, mainly influenced by DO, accounted for 12.5 % of the total variance.

DO, BOD and COD ($mg.L^{-1}$)

Statistically, significant variations ($P < 0.05$) were seen in concentrations of DO and BOD among sampling sites) (Table 2). The BOD was generally low in AG province's tributaries but was high in some sampling sites of CT. Similarly, CT showed the lowest COD in all sampling sites but was high in some sampling sites of CM from August to November during the rainy season.

Nitrite-NO_2^-($mg.L^{-1}$), nitrate-NO_3^-($mg.L^{-1}$) and phosphate-PO_4^{3-}($mg.L^{-1}$)

Currently, the maximum acceptable level of nitrite in water for aquaculture is 0.02 $mg.L^{-1}$ (Table 2). However, 34.2 % of sampling sites had a high NO_2^- concentration which exceeded this limit. During the dry season, the highest NO_2^- values were observed at sampling sites adjacent to industrial zones and residential areas. Similarly, during the rainy season, the highest NO_2^- values were seen at sites near aquaculture and residential areas. In addition, over 60 % of the sampling sites in ST exceeded the

Table 6. Pearson correlation coefficient (r) for the water quality variables in Soc Trang (ST) province in Mekong Delta during the study period.

Variables	Temp.	pH	DO	TSS	Alk.	BOD	COD	TAN	NO_2^-	NO_3^-	PO_4^{3-}	S^{2-}	Col.
pH	- 0.25***												
DO	*- 0.35****	*0.5****											
TSS	- 0.03	- 0.21*	- 0.09										
Alk.	- 0.017	- 0.13	- 0.18*	- 0.06									
BOD	- 0.12	0.07	0.24***	0.07	- 0.07								
COD	- 0.03	*- 0.4****	- 0.12	0.13	0.13	- 0.004							
TAN	0.14	- 0.24***	- 0.24***	- 0.15	0.18	- 0.10	0.21*						
NO_2^-	0.24***	*- 0.40****	- 0.23***	0.02	0.16	- 0.003	*0.34****	*0.41****					
NO_3^-	- 0.23***	0.20*	0.28***	0.34***	- 0.08	0.11	- 0.11	- 0.11	- 0.15				
PO_4^{3-}	- 0.10	0.13	0.07	- 0.19*	- 0.03	- 0.28***	0.12	0.11	- 0.09	0.03			
S^{2-}	- 0.25***	- 0.006	0.02	*0.30****	- 0.08	- 0.15	0.16	0.16	- 0.18*	0.13	0.16		
Col.	- 0.003	0.08	0.003	- 0.06	- 0.08	- 0.26***	0.18	0.19*	- 0.04	0.03	*0.38****	0.20*	
E. coli	0.08	- 0.07	0.04	0.06	- 0.06	0.06	0.19*	0.19*	0.06	0.10	- 0.06	- 0.07	*0.32****

Superscript: *** means that P < 0.01; and * means that *P* < 0.05.

Temp: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO^{2-}: Nitrite; NO^{3-}: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

Table 7. Pearson correlation coefficient (r) for the water quality variables in Bac Lieu (BL) province in Mekong Delta during the study period.

Variables	Tem.	pH	DO	TSS	Alk.	BOD	COD	TAN	NO_2^-	NO_3^-	PO_4^{3-}	S^{2-}	Col.
pH	*0.78****												
DO	0.23***	*0.50****											
TSS	- 0.18	0.14	0.12										
Alk.	0.17	0.04	0.01	- 0.05									
BOD	- 0.05	*0.30****	*0.38****	0.28***	0.07								
COD	0.11	0.01	- 0.09	0.17	*0.48****	- 0.01							
TAN	- 0.01	- 0.20*	- 0.14	- 0.14	0.30***	- 0.03	0.29***						
NO_2^-	- 0.05	0.17	- 0.13	- 0.09	0.08	- 0.09	0.17	0.34***					
NO_3^-	0.30***	0.10	- 0.041	- 0.20*	- 0.15	*- 0.36****	0.03	0.01	0.11				
PO_4^{3-}	0.09	- 0.07	- 0.29***	- 0.24***	- 0.05	- 0.12	- 0.13	- 0.009	0.07	- 0.01			
S^{2-}	- 0.02	0.007	- 0.02	*0.37***	0.11	0.09	0.14	- 0.05	- 0.02	- 0.10	- 0.09		
Col.	- 0.12	- 0.15	- 0.19*	- 0.06	0.12	0.02	- 0.10	0.09	0.001	- 0.49***	0.04	- 0.18*	
E. coli	- 0.04	- 0.21*	- 0.24***	- 0.19*	0.18*	0.08	- 0.04	0.17	0.14	- 0.28**	0.33***	- 0.13	*0.58****

Superscript: *** means that P < 0.01; and * means that *P* < 0.05.

Temp: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO^{2-}: Nitrite; NO^{3-}: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

Table 8. Pearson correlation coefficient (r) for the water quality variables in Ca Mau (CM) province in Mekong Delta during the study period.

Variables	Tem.	pH	DO	TSS	Alk.	BOD	COD	TAN	NO_2^-	NO_3^-	PO_4^{3-}	S^{2-}	Col.
pH	- 0.14												
DO	0.16	0.47***											
TSS	0.02	- 0.25***	0.14										
Alk.	0.39***	- 0.25***	0.01	0.08									
BOD	- 0.25***	0.34***	0.32***	- 0.06	- 0.20*								
COD	0.49***	- 0.18	- 0.04	0.03	0.13	- 0.19*							
TAN	0.07	- 0.23*	- 0.11	0.19*	0.37***	- 0.30***	0.16						
NO_2^-	0.27*	- 0.43***	- 0.15	0.17	0.23*	- 0.18*	0.36***	0.05					
NO_3^-	0.39***	- 0.27***	0.14	0.23*	0.29***	- 0.04	0.26***	- 0.07	0.27***				
PO_4^{3-}	- 0.12	- 0.24*	- 0.19*	- 0.06	- 0.07	- 0.13	0.03	- 0.14	- 0.07	0.23***			
S^{2-}	- 0.26***	0.05	0.09	0.14	0.08	0.26***	- 0.38***	- 0.27***	0.09	0.22***	0.07		
Col.	0.05	0.26***	0.008	- 0.10	- 0.07	- 0.03	0.006	0.01	- 0.22*	- 0.39***	- 0.22*	- 0.23*	
E. coli	0.15	0.17	- 0.05	- 0.05	0.04	- 0.01	0.14	0.24*	- 0.09	- 0.15	- 0.11	- 0.11	0.54***

Superscript: *** means that $P < 0.01$; and * means that $P < 0.05$.

Temp: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO^{2-}: Nitrite; NO^{3-}: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

Table 9. Principal component analysis results for the first four principal components in An Giang and Can Tho province in Mekong Delta.

Variables	An Giang (AG)				Can Tho (CT)			
	PC 1	PC 2	PC 3	PC 4	PC 1	PC 2	PC 3	PC 4
Temp.	- 0.257	- 0.343	0.413			- 0.271	0.116	0.665
pH	- 0.118	- 0.125	- 0.300	- 0.585		- 0.434	- 0.124	- 0.182
TSS	0.199	0.172	0.276	- 0.250	- 0.296		-0.367	
Alk.	0.144	- 0.571	0.164		0.553			0.147
DO	- 0.120	- 0.404	- 0.294	- 0.399	0.240	- 0.389	- 0.329	- 0124
BOD	0.427			- 0.221	0.138	- 0.365		
COD	0.389	0.118	0.251	- 0.202	- 0.126		- 0.551	0.226
TAN	- 0.369	0.259	0.310	- 0.160	- 0.136	0.248	- 0.204	0.179
NO_2^-		- 0.104	- 0.120	0.453	0.373	0.232	0.193	0.357
NO_3^-		- 0.373	0.476	- 0.128	0.163		0.401	- 0.381
S^{2-}	- 0.253	0.112	0.209	0.162	- 0.461	- 0.108	148	
PO_4^{3-}	0.443	0.121	0.168		- 0.232	0.253		- 0.252
Col.	- 0.169	0.360	0.212	- 0.177	- 0.375	- 0.372	0.196	0.194
E. coli	- 0.318	0.133	0.359	- 0.236	- 0.425		0.378	0.118
Variation (%)	17.9	15.3	12.6	11.0	18.6	15.2	11.8	9.0
Total	56.8 %				54.6%			

Temp.: Temperature; TSS: Total suspended solids; Alk.: Alkalinity; DO: Dissolved oxygen; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform. PC1 (BOD, COD and PO_4^{3-}), PC2 (DO and alkalinity), PC3 (temperature and NO_3^-) and PC4 (pH and NO_2^-).

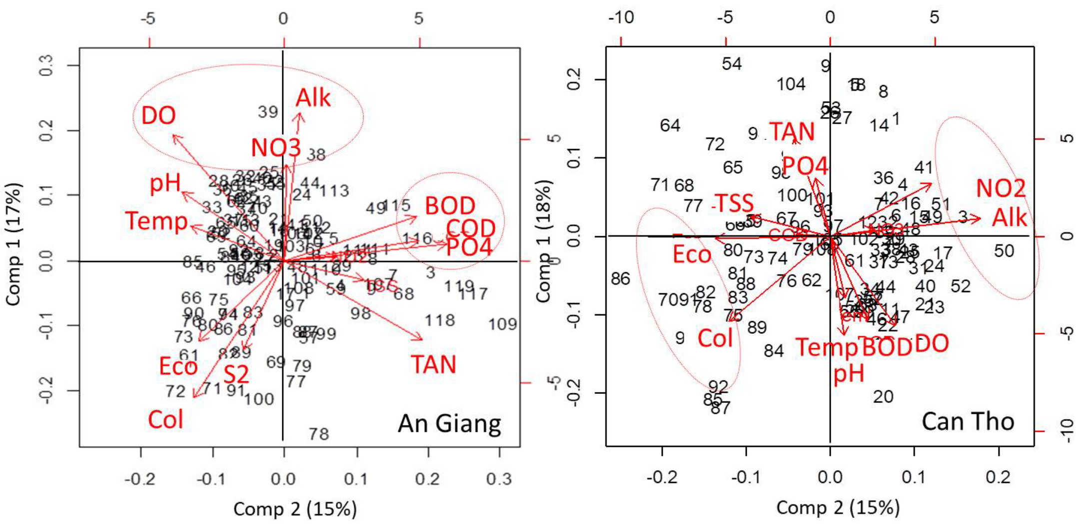

Fig. 3. Plot of the first two PC loading vectors of water quality variables in An Giang and Can Tho provinces in Mekong Delta. Temp.: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

acceptable NO_2 concentration (Table 2 and Table 3). These sites are mostly near super-intensive shrimp culture farms, residential areas and local wet markets. In contrast, the NO_3^- concentration was within the acceptable level of NTR. The PO_4^{3-} concentrations in CT and ST were higher than those in other provinces ($P < 0.05$).

S^{2-} (mg.L^{-1}), coliforms (MPN.100 mL^{-1}) and E. coli (MPN.100 mL^{-1})

The S^{2-} concentration varied widely throughout the sampling period, with the lowest levels in AG and the highest in ST (Tables 2 and 3). This parameter showed a high coefficient of variation (Fig. 2c) and was relatively high in BL and CM (Table 3). Generally, high S^{2-} concentrations in May, June and October were detected in ST, where there are many super-intensive shrimp farms, residential areas and wet markets. Similarly, BL had high S^{2-} concentrations, mainly during January, February and June.

The mean density of coliforms and *E. coli* fluctuated considerably among the sampling sites (Table 3 and Fig. 2d), with higher densities found in the rainy season compared to the dry season. In summary, NO_2^- and S^{2-} concentrations were beyond the limits recommended by NTR. However, S^{2-} concentrations exceeded the recommended limits permitted more frequently than NO_2^- concentrations, both temporally and spatially ($P < 0.05$). Furthermore, S^{2-} concentrations were higher in the dry season than in the rainy season, and in the coastal areas, the values were also higher than those in the inland areas ($P < 0.05$).

Discussion

Spatial and temporal variation in temperature and pH were small across all sampling sites, and both temperature (29–30 °C) and pH (6.5–7.5) were well within the range considered to be most suitable for tropical aquaculture species, which is 28–32 °C and pH 6.0–7.8 (Boyd, 1998). However, most other water quality parameters were highly variable, spatially and temporally, and at some sites, the water quality parameters were at levels close to or above the acceptable level for aquaculture. There seems to be no clear agreement on an acceptable upper limit for BOD in aquaculture, with some authors suggesting that a BOD of up to 30 mg O_2.L^{-1} is acceptable (Boyd, 1998, 2003). In contrast, others consider 10 mg O_2.L^{-1} an acceptable upper limit (Trinh, 1997). The maximum value of BOD recorded in this study was only 7.6 mg.L^{-1}, (Table 3), which was well within limits specified by NTR. (QCVN 38:2011/BTNMT (MONE, 2011) and QCVN 08-T:2015/BTNMT (MONE, 2015).

However, Fridah et al. (2021) found high and somewhat variable concentrations of BOD and total coliforms along the Hau River. The researchers also observed DO levels ranging from 3.7 to 5.7 mg.L^{-1}, with the lowest levels in intensive aquacultural regions, which correspond with CT9 in the present study. Most physicochemical parameters in AG province were within the acceptable range of NTR, except for S^{2-} and NO_2^-, which fluctuated highly both temporally and spatially.

Coefficient of variation of variables

The study showed significant variation in several variables (Table 3 and Figs. 2b, 2c, 2d). Notably, high variability was observed in PO_4, NO_2, S_2, NO_2, NO_3, *E. coli*, and coliform. However, only PO_4, S_2, NO_2 and NO_3 exceeded the threshold levels specified in the NTR. The high temporal and spatial fluctuations in these parameters that exceed NTR appear to be associated with anthropogenic activities such as sewage

Table 10. Results from the Principal Component Analysis for the first four principal components in Soc Trang, Bac Lieu and Ca Mau province.

Variables	Soc Trang (ST)				Bac Lieu (BL)				Ca Mau (CM)			
	PC 1	PC 2	PC 3	PC 4	PC 1	PC 2	PC 3	PC 4	PC 1	PC 2	PC 3	PC 4
Tem.	0.292	0.110	0.136		- 0.241	0.102	*- 0.455*	0.368	0.226	- 0.383	0.286	*0.485*
pH	*- 0.429*	- 0.139	0.243		- 0.367	- 0.168	- 0.318	0.337	*- 0.441*		0.400	
TSS		0.265	*- 0.528*	0.131	- 0.130	- 0.378		- 0.300	0.240		0.161	*- 0.490*
Sal.	- 0.124	*0.408*	- 0.195	0.115	*- 0.428*	0.192				- 0.133		- 0.326
Alk.	0.178	0.148		0.249	0.131	- 0.136	*- 0.510*	- 0.148	0.314	- 0.334	0.148	
DO	*- 0.41*			- 0.289	- 0.331	- 0.261	- 0.118	- 0148			*0.663*	
BOD	- 0.145	0.377		- 0.177		*- 0.512*						
COD	0.277	- 0.107	- 0.388	- 0.399			*- 0.445*	- 0.418				
TAN	0.372								0.103	- 0.446	- 0.179	- 0.321
NO_2^-	0.383	0.189	- 0.106	- 0.163					0.386	- 0.119		
NO_3^-	- 0.331	0.154	- 0.358						*0.436*		0.300	0.208
S^{2-}	- 0.115	- 0.228	*- 0.426*	0.335	- 0.121	- 0.237		- 0.305	0.125	0.331	0.252	- 0.424
PO_4^{3-}		*- 0.47*		0.143	0.207	0.150		0.279				
Col.		*- 0.490*	- 0.240	- 0.226	*0.358*	- 0.199		0.297	- 0.381	- 0.337		
E.coli			- 0.240	*- 0.639*	*0.393*		- 0.117	0.298	- 0.227	- 0431		
Variance (%)	20.9 %	13.2 %	10.8 %	9 %	20.9 %	14.2 %	12.1 %	11.5 %	19.9 %	15.5 %	12.5 %	9.0 %
Total	53.9%				58.7%						56.9%	

Temp.: Temperature; TSS: Total suspended solids; Sal.: Salinity; Alk.: Alkalinity; DO: Dissolved oxygen; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform. PC1 (BOD, COD and PO_4^{3-}), PC2 (DO and alkalinity), PC3 (temperature and NO_3^-) and PC4 (pH and NO_2^-).

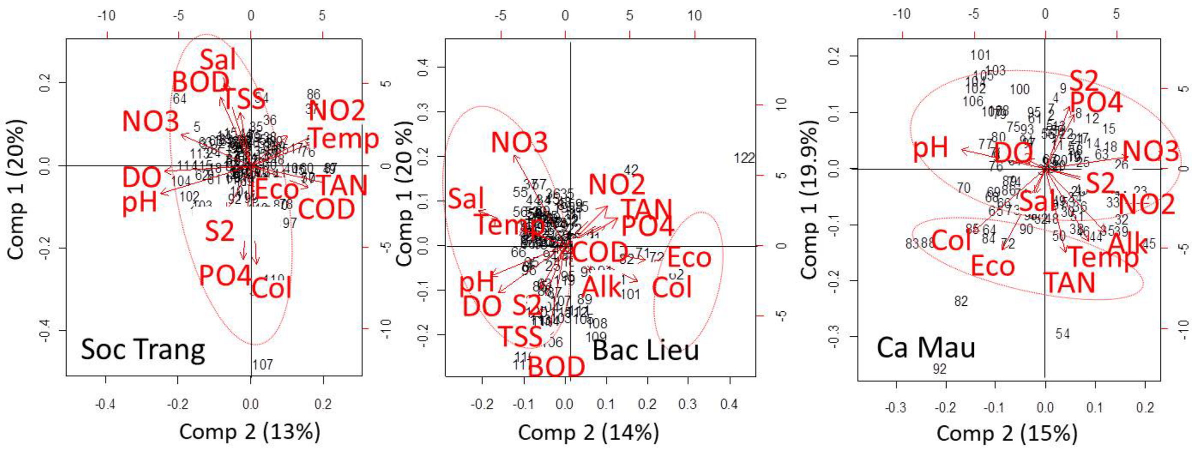

Fig. 4. Plot of the first two PC loading vectors of 15 variables of water quality in Soc Trang, Bac Lieu and Ca Mau provinces including Temp.: Temperature; DO: Dissolved oxygen; TSS: Total suspended solids; Alk.: Alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TAN: Total ammonia nitrogen; NO_2^-: Nitrite; NO_3^-: Nitrate; PO_4^{3-}: Phosphate; S^{2-}: Sulphide; Col.: Coliform.

discharge around wet markets and residential areas, fertiliser application during rice cropping, and pond excavation and harvesting in aquaculture.

Waibel et al. (2017) reported that shrimp production is influenced by various factors such as physicochemical parameters and interactions with rainfall, temperature, salinity and pH. These factors could lead to the build-up of toxic compounds, causing negative impacts on shrimp health by reducing shrimp resistance to diseases and increasing susceptibility to infectious diseases (Casani, 2006; Tendencia et al., 2011). Me et al. (2014) confirmed that water quality deteriorated with high levels of organic indicators such as COD and BOD, and highly fluctuating levels of TAN (Fig. 2c). Furthermore, a high level of TAN frequently harms aquatic animal health, and its toxicity depends on temperature and pH (Robinette, 1983). Excessive nitrite accumulation in water can occur due to the nitrification process. This phenomenon is attributed to a significant increase in nitrite build-up due to a drastic increase in TAN, stimulating ammonia-oxidising bacteria. As a result, nitrite accumulates faster than nitrite-oxidising bacteria can convert to nitrate (Boyd and Tucker, 2014).

Pearson correlation coefficient

In ST province, a significant positive correlation was observed between NO_2^- and TAN and the impact of TAN on aquatic organisms is associated with pH and temperature (Robinette, 1983). A study by Nguyen et al., (2014) revealed that the pH in the striped catfish pond was between 6.7–7.5 and decreased gradually toward the end of the culture cycle. Maintaining a suitable pH helps prevent the toxicity of NH_3. According to Boyd (1998), tropical fish thrive in temperatures and pH ranging from 28–32 °C and 6.0–7.8, respectively. Fluctuation of DO, BOD, COD, TAN, NO_3^- and alkalinity was observed (Table 3 and Fig. 2), which were closely associated with aquaculture activities.

Ut et al. (2016) identified potential eutrophication problems characterised by high nitrogen and phosphorus concentrations in both culture ponds and water sources areas where striped catfish farming takes place. In addition, fish culture is more susceptible to disease problems in the rainy season due to sudden changes in water quality caused by heavy rainfall. Chemicals and drugs to prevent diseases during this period could contribute to inorganic pollution. Moreover, although exchanging water is a common practice to prevent the deterioration of water quality from leftover feed and fish wastes, many aquaculture farmers lack awareness regarding waste management practices. Furthermore, wastewater discharge from seafood processing plants contains large amounts of organic matter, causing serious concerns for the aquatic environment (De Silva and Phuong, 2011).

The density of coliforms and *E. coli* during the rainy season was higher than in the dry season across all sampling sites, and their sources differed and were more widespread in the rainy season. However, their densities were insufficient to affect the aquatic animal health. Water temperature is one of the most important physical factors affecting the composition and bacterial counts of coliforms, and *E. coli* (Humbert et al., 2009), and their abundance is positively correlated with water temperature, especially above 30 ºC (Tatsuya et al., 2017). The presence of coliforms and *E. coli* reflects the discharge of untreated sewage close to the sampling sites.

Principal component analysis

Statistical spatial analyses such as PCA provides valuable insights into group relationships from water quality parameters (Ying, 2005). In the case of CT province, the first four PCs, as shown in Table 9 and Figure 3, highlights the significant changes due to the development of aquaculture, agriculture, and the discharge of sewage from residential areas. These PCs relating to chemical, physical and biological parameters indicated that the region had undergone significant changes due to the development of aquaculture, agriculture, and sewage discharge from residential areas.

The influence of pH and Alk. on the toxicity of most water quality parameters is well documented (Boyd et al., 2016). In AG province, the results showed that PC1 was inversely correlated between Temp. and Alk., the 2nd PCs positively correlated with Alk. vs DO, and the 3rd PC was related to physical parameters such as Temp. and Alk. as well as chemical parameters, including DO and NO_3^-, respectively, with a low correlation. Furthermore, in an earlier study in the Hau River, the PCA analysis of water quality found that Temp., DO, pH, Alk., Sal., TAN, TSS, BOD, NO_3^-, PO_4^{3-} and total coliforms were all key indices of water quality, as they significantly influenced the surface water quality at various sampling sites (Mutea et al., 2021).

According to Ut et al. (2016), the region of striped catfish in the Mekong Delta showed low levels of BOD and COD in organic matter, while ponds and rivers serving as a water source for aquaculture showed high concentrations of nitrogen and phosphorus. This indicates a potential pollution problem in the region. Nhut (2016) also confirmed that water quality at striped catfish farms in the Mekong Delta was related to nutrient utilisation efficiencies and waste discharge and that issues like solid waste removal from ponds, water exchange, and pellet quality. These factors have a significant impact on water quality in the region.

The high BOD was found mainly in the coastal provinces in the dry season due to limited water exchange and the poor irrigation system. According to Cat et al. (2006), water containing BOD concentrations greater than 5 mg $O_2.L^{-1}$ is considered polluted. Overall, all water quality parameters seem to meet the acceptable limits for aquaculture, except NO_2^- and S^{2-}, which exceeded the recommended values by NTR.

Hydrogen sulphide (H_2S) is a toxic gas produced under anoxic and acidic conditions by microorganisms, and high concentrations lead to mortality in aquatic animals (Kutty, 1987). Freshwater fish species have been reported to tolerate H_2S concentrations up to 0.02–0.05 $mg.L^{-1}$ (Rajts and Shelley, 2020). In the present study, S^{2-} concentrations were higher than acceptable levels at most sampling periods in ST, BL and CM provinces. Most of these sites are near zones of intensive shrimp farming, residential areas and wet markets or associated with poor irrigation infrastructure, and the organic matter discharged from these areas could be a potential risk to surface water quality.

In CT province, S^{2-} concentrations were relatively high because these sites are also near the zone of intensive striped catfish culture, seafood processing facilities, and residential and industrial areas. In addition, NO_2^- concentrations also exceeded the acceptable limits of NTR during the dry season samplings in January, February, March, April, and May (Fig. 5). In fact, a gradual increase in eutrophication occurs regularly in fish farming ponds from the middle to the end of the culture period.

The accumulation of nutrient loads in fish ponds derived mainly from the leftover feed and faeces may pose serious risks to environmental health if untreated water is discharged directly into nearby the environment. According to the NTR NO_2^- concentrations should be less than 0.05 $mg.L^{-1}$ in aquaculture systems. However, some authors suggested that NO_2^- concentrations in aquaculture ponds should be less than 1.0 $mg.L^{-1}$, as exceeding this level can lead to inorganic eutrophication and deplete DO concentration in water (Boyd et al., 2001; Timmons et al., 2002). In inland provinces, surface water quality in AG province was much better than in other provinces. This could be because AG is located in the upstream section of the Hau River, with abundant water flows, contributing to good water exchange and flushing.

In contrast, water pollution was more severe during the dry season in CT and other provinces. The water pollution was attributed partly to the reduction in water flow downstream from AG, and partly because CT and ST situated further downstream receive water that has already been polluted by agriculture, aquaculture, industrial and domestic wastes upstream. Additionally, surface water quality in ST province was severely impacted by nutrient enrichment from shrimp culture activities. The concentration of NO_2^- in June at the sampling site ST7 was correlated with pH, and NO_2^- concentration beyond the acceptable levels of NTR. In addition, S^{2-} concentrations in ST province were high in January, May and October as the intensive shrimp culture, agriculture and residential areas, and wet markets surround the locations.

The high NO_2^- and S^{2-} concentrations at the sampling sites in tributaries of CT were typical of those in small tributaries of the Hau River, characterised by low water exchanges. A similar result was also observed in May, June and November in CT located along the Hau River, which has intensive aquaculture and residential areas. The NO_2^- concentrations did not meet the acceptable levels of NTR during the sampling in January, March, and April at all sites. Similarly, S^{2-} concentration was beyond acceptable levels at all sampling sites (Fig. 5). H_2S can be formed in anaerobic sediment by sulphate-reducing bacteria and released into the water column. This gas is extremely toxic to

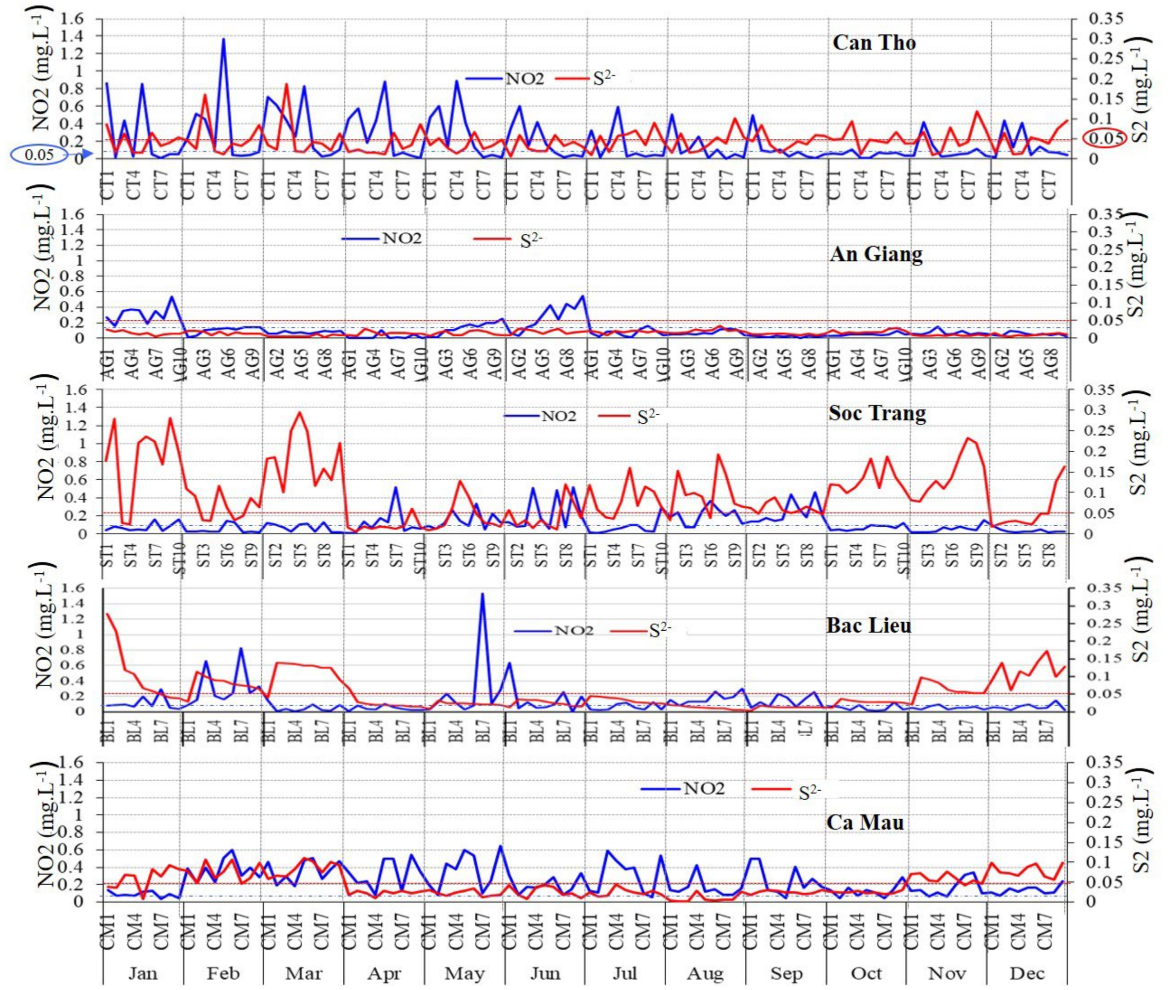

Fig. 5. Fluctuations of nitrite (NO_2^-) and sulphide (S^{2-}) concentration observed at the five sampling sites in the Mekong Delta during the study period.

aquatic animals and can kill aquatic animals directly; the effect often results in a depressed immune response increasing susceptibility to infectious diseases.

Water supply is often the most common water-quality stressor. In contrast, low pollution levels are less likely to affect aquatic animals because Aquaculture facilities located at sites with minimal pollution are less likely to be affected. The water quality variables that could most likely cause excessive stress or mortality to aquatic animals when they are beyond the optimal concentration include water temperature, salinity, pH, dissolved oxygen, ammonia nitrogen, nitrite, carbon dioxide, and hydrogen sulphide (Boyd, 2017).

However, the variation in surface water quality during the study across the five provinces could be attributed to the discharged source originating from the surrounding habitats. These sources consisted of suspended solids and rapid fluctuations in salinity levels, which undergo rapid changes due to heavy rainfall. Thus, the short-term changes in physicochemical parameters of water quality could be attributed to the rainy season. The physical parameters strongly influence the whole environment's components, including the chemical and biological factors. In addition, human activities also affect water quality changes (Norman et al., 2006).

Intensive shrimp culture, agricultural practices, and the discharge of waste from residential areas and wet markets greatly influenced water quality in the Soc Trang (ST) coastal province. These factors contributed to elevated levels of toxic S^{2-} and NO_2^- in ST. Similarly, in BL, another coastal province, the surface water quality was affected by effluent discharged from shrimp farms and their interaction with natural factors such as temperature and pH. According to the findings of Oanh et al. (2022), the occurrence of white spot disease syndrome in shrimp in the VMD was observed from October to December, which coincided with the rainy season when temperatures of 29-30.5°C were considered suitable for aquaculture. Hence, the rapid fluctuations in water quality, leading to animal stress, could cause the disease outbreak.

The results in BL were closely related to waste discharges from intensive shrimp farms and sewage discharge from the residential areas. Differences in water quality between BL and CM were generally insignificant because both provinces share water from the same river (Ganh Hao River) and have similar shrimp farming practices and communal habits. The quality of water sources in these areas was affected by extensive shrimp culture activities and sewage discharge from local communities. Moreover, the water quality problem could also be due to poorly developed canals and irrigation infrastructures in which a low retention rate or high accumulation of pollutants may occur compared to the advanced development of shrimp culture. However, intensive shrimp culture is usually carried out by large companies and cooperative farms consisting of groups of farmers, which have the financial and technical resources to manage water quality through chemical treatments and water recirculation, so it has a less environmental impact. By contrast, individual farmer's farms are often smaller in scale, and they have less technical knowledge and fewer resources to manage water quality effectively without water exchange. Thus, they often release water with high COD and BOD, leading to a deterioration in water quality in adjacent waterways.

The pollution from anthropogenic activities is generally considered small-scale and of limited magnitude, leading to the belief that it does not have serious adverse impacts on water quality. However, ACIAR's study (2020) focused on rice-shrimp farming activities in the VMD and revealed that eutrophication, characterised by high nutrient loads, was not attributed to rice-shrimp farming itself. Instead, it was attributed to polluted canals or other human activities, including sewage discharge.

In practical terms, rivers exhibit spatial heterogeneity, resulting in significant differences in their characteristics, such as depth, width, and areas affected by diverse activities in their surroundings. The current water sampling schemes may not sufficiently capture the spatial complexity or provide adequate or accurate representation, challenging the notion that a river can be considered a uniform and homogeneous body (Casper et al., 2012).

Conclusions

During the study period, the surface water quality in the intensive aquaculture areas of the Mekong Delta was highly variable, with most variables showing correlation coefficients of - 0.5 to 0.5. While most parameters were in the acceptable range, NO_2^- and S^{2-} were beyond the acceptable levels across all sampling sites throughout the study period. These are two critical factors influencing water quality for aquaculture. To mitigate adverse impacts on aquaculture in the Mekong Delta, implementing regular monitoring of water parameters using mapping techniques to predict any trend of water quality variation can be a valuable approach to detect and prevent adverse impacts on aquaculture.

Acknowledgements

This research was partly funded by the Can Tho University Improvement Project VN14-P6, supported by a Japanese ODA loan.

Conflict of interest: The authors declare that they have no conflict of interest.

Author contributions: Tran Van Viet: Research designing, conducting, data analysing and manuscript preparation. Au Van Hoa: Field sampling. Huynh Truong Giang: Water quality analysis. Vu Ngoc Ut: Research designing, supervising, reviewing and editing the manuscript.

References

Abdelrahman, H.A., Abebe, A., Boyd, C.E. 2019. Influence of variation in water temperature on survival, growth and yield of Pacific white shrimp *Litopenaeus vannamei* in inland ponds for low-salinity culture. Aquaculture Research 50:658–672. https://doi.org/10.1111/are.13943

ACIAR. 2020. Improving the sustainability of rice-shrimp farming systems in the Mekong Delta, Vietnam, ACIAR GPO Box 1571 Canberra ACT 2601 Australia Number project: SMCN/2010/083, https://www.aciar.gov.au/sites/default/files/2021-11/final-report-SMCN-2010-083_0.pdf (Accessed 12 March 2022).

APHA. 2017. Standard methods for the examination of water and wastewater. 23rd Edition. American Public Health Association, Washington, DC. 1796 pp.

Boyd, C.E. 1998. Water quality for pond aquaculture. Department of Fisheries and Allied Aquacultures, Auburn University, Alabama. 39 pp.

Boyd, C.E. 2001. Water quality standards: Biochemical oxygen demand. https://www.aquaculturealliance.org/advocate/water-quality-standards-dissolved-oxygen/ (Accessed 25 March 2022).

Boyd, C.E. 2003. Guidelines for aquaculture effluent management at farm-level. Aquaculture 226:101–112. https://doi.org/10.1016/S0044-8486(03)00471-X

Boyd, C.E. 2017. General relationship between water quality and aquaculture performance in ponds. In: Fish diseases: Prevention and control strategies, Jeney, G. (Ed.), Elsevier Inc., pp. 147–166. https://doi.org/10.1016/B978-0-12-804564-0.00006-5

Boyd, C.E., Tucker, C.S. 1998. Pond aquaculture water quality management. Springer, New York. 700 pp.

Boyd, C.E., Tucker, C.S. 2014. Handbook for aquaculture water quality. Craftmaster Printers Inc., Auburn. 439 pp.

Boyd, C.E., Tucker, Somridhivej, C.B. 2016. Alkalinity and hardness: Critical but elusive concepts in aquaculture. Journal of the World Aquaculture Society 47:6–41. https://doi.org/10.1111/jwas.12241

Casani, S., Leth, T., Knchel, S. 2006. Water reuse in a shrimp processing line: Safety considerations using a HACCP approach. Food Control 7:540–550. https://doi.org/10.1016/j.foodcont.2005.03.002

Casper, A.F., Dixon, B., Steimle, E.T., Hall, M.L., Conmy, R.N. 2012. Scales of heterogeneity of water quality in rivers: Insights from high resolution maps based on integrated geospatial, sensor and ROV technologies. Applied Geography 32:455–464. https://doi.org/10.1016/j.apgeog.2011.01.023

Cat, L.V., Nhung, D.T.H., Cat, N.N. 2006. Water for aquaculture - Quality and measures for improving quality. Science and Technology Publishing House, Viet Nam. 414 pp. (in Vietnamese).

De Silva, S.S., Phuong, N.T. 2011. Striped catfish farming in the Mekong Delta, Vietnam: A tumultuous path to a global success. Reviews in Aquaculture 3:45–73. https://doi.org/10.1111/j.1753-5131.2011.01046.x

Department of Agriculture and Rural Development of AG (DARD of AG). 2021. Striped catfish increased lightly. https://baoangiang.com.vn/san-luong-ca-tratang-nhe-a298640.html (Accessed 15 March 2021).

FAO. 2019. Risk management practices of small intensive shrimp farmers in the Mekong Delta of Viet Nam https://www.fao.org/3/ca6702en/ca6702en.pdf (Accessed 25 March 2022).

Fowler, J., Cohen, L. 1992. Practical statistics for field biology. John Wiley and Sons Ltd., England. 259 pp.

Greenacre, M., Michael, G. 2010. Biplots in practice. https://www.fbbva.es/wp-content/uploads/2017/05/dat/DE_2010_biplots_in_practice.pdf (Accessed 29 March 2022).

Humbert, J.F., Dorigo, U., Cecchi, P., Le B. B., Debroas, D., Bouvy, M. 2009. Comparison of the structure and composition of bacterial communities from temperate and tropical freshwater ecosystems. Environmental Microbiology 11:2339–2350. https://doi.org/10.1111/j.1462-2920.2009.01960.x

Jolliffe, L.T. 2002. Principal component analysis. 2nd Edition. Springer, New York. 488 pp. https://doi.org/10.1007/b98835

Jolliffe, L.T., Cadima, J. 2016. Principal Component Analysis: A review and recent development. Philosophical Transactions of the Royal Society A 374:20150202. https://doi.org/10.1098/rsta.2015.0202

Khatoon, N., Khan, A.H., Masihur, R.M., Pathak, V. 2013. Correlation study for the assessment of water quality and its parameters of Ganga River, Kanpur, Uttar Pradesh, India. IOSR Journal of Applied Chemistry 5:80–90. https://doi.org/10.9790/5736-0538090

Kutty, M.N. 1987. Site selection for aquaculture: Chemical features of water. Food and Agriculture Organization of the United Nations, ARAC/87/WP/12-9. 40 pp.

Loska, K., Wiechuła, D. 2003. Application of principal component analysis for the estimation of source of heavy metal contamination in surface sediments from the Rybnik Reservoir. Chemosphere 51:723–733. https://doi.org/10.1016/S0045-6535(03)00187-5

Me, K., Liao, L., Zhu, Lu, P., Wang, H., Dahlgren, R.A., Zhang, M. 2014. Evaluation of spatial-temporal variations and trends in surface water quality across a rural-suburban-urban interface. Environmental Science and Pollution Research 21:8036– 8051.

Ministry of Agricultural and Rural Development (MARD). 2019. Status of aquaculture and fisheries in 2019 and plan for 2020. Annual report. 16 pp.

Ministry of Natural Resources and Environment (MONRE). 2011. National technical regulation on surface water quality for protection of aquatic life (QCVN 38: 2011/BTNMT), Hanoi, Vietnam. (in Vietnamese).

Ministry of Natural Resources and Environment (MONRE). 2015. National technical regulation on surface water quality (QCVN 08-2015/BTNMT), Hanoi, Vietnam. (in Vietnamese).

Mutea, F.G. Nelson, H.K. Hoa, A.V., Giang, H.T., Ut, V.N. 2021. Assessment of water quality for aquaculture in Hau River, Mekong Delta, Vietnam using multivariate statistical analysis. Water 13:3307. https://doi.org/10.3390/w1322330

Nguyen, P.Q., Cong, N.V., Phu, T.Q. 2014. Fluctuation of some water parameters in striped catfish (*Pangasianodon hypophthalmus*) intensive culture ponds. Science Journal of Can Tho University 34: 128–136. (in Vietnamese).

Nhut, N. 2016. Improving sustainability of striped catfish (*Pangasianodon hypophthalmus*) farming in the Mekong Delta, Vietnam through recirculation technology. PhD thesis, Wageningen University, 180 pp. https://doi.org/10.18174/394644

Norman, P., Michel, M., Deborah, V.C. 2006. Effects of human activities on water quality. In: Encyclopedia of hydrological sciences, Anderson, M.G., McDonnell, J.J. (Eds.), John Wiley and Sons, pp. 1–17. https://doi.org/10.1002/0470848944.hsa096

Oanh, Đ.T., Phu, T.Q., Phuong N.T. 2022. Disease incidence in shrimp farms located in east coastal region of the Mekong Delta, Viet Nam. Can Tho University Journal of Science 14:37–45, https://doi.org/10.22144/ctu.jen.2022.019

Rajts, F., Shelley, C.C. 2020. Guidelines for managing aeration and water quality in fish hatcheries and nurseries in Bangladesh. Penang, Malaysia. World Fish. Guidelines: 2020-35. https://doi.org/10.13140/RG.2.2.31034.82889

Robinette, J.R. 1983. Ammonia, nitrite, and nitrate. In: Water quality in channel catfish ponds. Southern Cooperative Series Bulletin 290, Mississippi Agricultural and Forestry Experiment Station, Mississippi State University, Mississippi State, MS, pp. 28–34.

Shine, J.I., Ford, R.T. 1995. Multivariate statistical examination of spatial and temporal patterns of heavy metal contamination in New Bedford Harbor marine sediments. Environmental Science and Technology 29:1781–1788. https://doi.org/10.1021/es00007a014

Simeonov, V., Stratis, J.A., Samara, C., Zachariadis, C., Voutsa, D., Anthemidis, A., Sofoniou, M., Kouimtzis, T. 2003. Assessment of the surface water quality in Northern Greece. Water Research 37:4119–4124. https://doi.org/10.1016/S0043-1354(03)00398-1

Svobodova, Z., Lloyd, R., Máchová, J., Vykusova, B. 1993. Water quality and fish health. EIFAC Technical Paper. No. 54. FAO, Rome. 59 pp.

Tatsuya, N., Hoa, T.T.T., Kazuo, H., Minae, W., Megumi, A., Atsushi, H., Joon, W., Phu, T.M., Shuhei, U., Yoshinori, S., Kazumasa, H., Phuong, N.T., Yoshimasa, Y. 2017. Water metagenomic analysis reveals low bacterial diversity and the presence of antimicrobial residues and resistance genes in a river containing wastewater from backyard aquacultures in the Mekong Delta, Vietnam. Environmental Pollution 222:294–306. https://doi.org/10.1016/j.envpol.2016.12.041

Tendencia, E., Verreth, J.A.J. 2011. Temperature fluctuation, low salinity, water microflora: Risk factors for WSSV outbreaks in *Penaeus monodon*. The Israeli Journal of Aquaculture-Bamidgeh 63:548. http://hdl.handle.net/10862/1618

Timmons, M.B., James, M.E., Fred, W.W., Steven, T.S., Brian, J.V. 2002. Recirculating aquaculture systems. 2nd Edition. NRAC Publication No. 01-002, Cayuga Aqua Ventures, LLC. 769 pp.

Trinh, L. 1997. Water environment control and monitoring. Science and Technology Publishing House. 231 pp. (in Vietnamese).

Ut, V.N., Giang, H.T., Phu, T.Q., Morales, J., Phuong, N.T. 2016. Assessment of water quality in catfish (*Pangasianodon hypophthalmus*) production systems in the Mekong Delta. Can Tho University Journal of Science 3:71–78. https://doi.org/10.22144/ctu.jen.2016.026

Vietnam Association of Seafood Exporters and importers (VASEP). 2021. https://vasep.com.vn/san-pham-xuat-khau/ca-tra/tong-quan-nganh-ca-tra (Accessed 30 March 2022).

Vietnam General Statistics Office-GSO. 2020. Statistical data - General Statistics Office of Vietnam. www.gso.gov.vn (Accessed 22 July 2022).

Vietnam General Statistics Office-GSO. 2023. Statistical data - General Statistics Office of Vietnam www.gso.gov.vn (Accessed 01 March 2023).

Waibel, H.P.T.H., Völker, M. 2017. Farmers' perceptions of and adaptations to climate change in Southeast Asia: The case study from Thailand and Vietnam. In: Climate smart agriculture, Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S., Branca (Eds.), Springer: Cham, Switzerland, pp. 137–160.

Wilbers, G.J., Becker, M., Nga, L.T., Sebesvari, Z., Fabrice, G., Renaud, F.G. 2014. Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam. Science of The Total Environment 485-486:653–665. https://doi.org/10.1016/j.scitotenv.2014.03.049

Ying, O. 2005. Evaluation of river water quality monitoring stations by principal component analysis. Water Research 39:2621–2635. https://doi.org/10.1016/j.watres.2005.04.024