
**HYDROCHEMISTRY, HYDROBIOLOGY:
ENVIRONMENTAL ASPECTS**

The Interactive Effects of Natural Factor and Pollution Source on Surface Water Quality in the Lower Mekong River Basin, Southwestern Vietnam

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Abstract—Surface water quality could be interactively affected by the natural factor (seasonal variation) and human pollution source (industrial, agricultural, and residential sources). The current study was conducted in Hau Giang province in southwestern Vietnam (1) to investigate the interactive effect of natural factor and human pollution source and (2) to identify potential mechanisms related to the effects on quality parameters of surface water. Water samples were taken from 29 points in 2013, 2014, and 2015 in the dry and rainy seasons in industrial, agricultural, and residential zones to measure 11 parameters. While pH, NH_4^+ , PO_4^{3-} , and temperature were significantly higher in the dry than the rainy season, NO_3^- , dissolved oxygen (DO), and Fe were significantly affected by both experimental factors. The interactive effect of the two factors on biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) was significant. Residential and industrial zones had higher BOD_5 and COD concentrations in the dry than in the rainy season, while agricultural zones showed no differences between the two seasons. The dilution effect in the rainy season and concentrative effect in the dry season may explain the seasonal difference in the residential and industrial zones. Meanwhile, agricultural runoff could be a mechanism to bring more organic matter to the sampling points during the rainy season, neutralizing the dilution effect. In conclusion, pollution sources such as agricultural production, residential areas, and industrial manufacturing may directly affect surface water quality, while, the seasonal variation could modify the impacts by introducing dilution and runoff effects.

Keywords: water quality, seasonal variation, anthropogenic influences, pollution sources

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INTRODUCTION

Surface freshwater quality is of global concern due to its significant impact on various aspects of human and natural ecosystems. This is especially true in developing countries because surface water from rivers and canals support millions of people by providing functions, including transportation, agricultural production (rice production, aquaculture), tourism, recreation, and hydropower production. Raschid-Sally and Jayakody [24] even reported that many developing countries also used polluted water for agricultural production, threatening the health of consumers. Surface water quality could be significantly affected by natural factors (seasonal variation) and anthropogenic impacts (discharge of domestic and industrial wastewater and agricultural production) [2].

The southwestern delta of Vietnam is the lower basin of the Mekong River, one of the biggest rivers in the world, flows across six riparian countries including China, Myanmar, Thailand, Cambodia, and Vietnam. With a length of 4909 km and an annual capacity of 475 km³, the Mekong River provides aquatic resources, such as freshwater, fish, rice, and aquatic ecosystems for almost 60 million people [8, 12]. Unfortunately, water quality in the Mekong River is degraded [8], threatening the environment and the river-dependent people living in the lower basin. The authors concluded that surface water in the lower Mekong River basin in southwestern Vietnam was classified as moderate- to poor- quality, with high nutrient concentrations and dissolved solid contents; additionally, tributaries (both branch rivers and man-made canals) were more polluted than the main river

stream. This means that local pollution sources may contribute to poorer water quality in the tributaries of the Lower Mekong River basin in southwestern Vietnam that needs more study.

In general, local anthropogenic impacts, such as agricultural activities, urbanization, and industrial parks, were identified as the most important pollution sources affecting surface water quality [38]. Moreover, surface water quality in an area is likely affected by seasonal variation. In southwestern Vietnam, there are two distinct seasons the dry and rainy seasons, both of which may influence the surface water quality of the local rivers and canals. High rainfall in the rainy season could dilute and/or wash out local pollutants, physically reducing pollutant concentrations in surface water or cause runoff from fields, roads, and land surfaces, adding pollutants to the surface water. In contrast, low rainfall during the dry season typically brings less water to the studied area, minimizing the dilution effect on the concentration of the locally formed pollutants and degrading water quality.

There are three primary human impacts polluting surface water in southwestern Vietnam, including agricultural, industrial production, and residential activities. The discharges of wastewater from these activities were also identified as three main types of pollutants potentially affecting surface water quality in general [15]. Domestic wastewater is characterized by high contents of organic matter (BOD and COD), ortho-phosphorous, and NH_4^+ , originating from toilets, kitchens, washing, etc. [6]. As a result, the discharge of this wastewater may pollute surface water with high concentrations of dissolved nutrients and organic matter content. On the other hand, the characteristics of industrial wastewater greatly depend on the type of industry, for example, chemical production, food processing, and the textile industry, which each produce wastewater with different properties. Nevertheless, the two-wastewater types undergo required treatment before being discharged into the river. How pollutant the local surface water is dependent on the properties of the materials being discharged.

Agricultural activities are another important source of surface water pollution. In the US, agricultural activities were identified as the primary factor explaining poor surface water quality [32]. Agricultural activities in the lower Mekong River basin in Vietnam primarily include crop production. It is dominated by paddy rice cultivation, with smaller proportions of corn, watermelon, and vegetable production. Soil manipulations, such as plowing and harrowing, and applications of animal manure, inorganic fertilizers, and pesticides may lead to poor surface water quality due to runoff or erosion from crop fields. Drainage from the crop fields was also recognized as a mechanism of transporting nutrients and dissolved particulate matter to surface water, warranting specific man-

agement recommendations [10]. Different from the domestic and industrial effluents, agricultural runoff is not subject to treatments before being discharged. However, agricultural management, such as an application of precision agriculture [4], may reduce pollutant loads to surface water. Therefore, examining surface water quality parameters surrounding the discharge points (for the industrial and domestic zones) or within the runoff areas may reveal the pollution status of the outputs from the three impacts.

The two factors described above, pollution source and seasonal variation, potentially affect surface water quality in the lower Mekong River basin in southeastern Vietnam. The interactive effects of these two factors are also important and should be clarified. Due to similar conditions, these impacts may affect all provinces located within the lower Mekong River basin. Nevertheless, few studies are addressing the effects. As such, the current study was conducted in Hau Giang province, centrally located in the lower Mekong River basin in southwestern Vietnam, (1) to investigate the interactive effect of natural factor (seasonal variation) and human pollution source (industrial, agricultural, and residential sources) and (2) to identify potential mechanisms related the effects on quality parameters of surface water.

MATERIALS AND METHODS

Studied Area

The current study was conducted in Hau Giang province, located at $105^{\circ}19'39''$ – $105^{\circ}53'49''$ E and $9^{\circ}34'59''$ – $9^{\circ}59'39''$ N, within the lower Mekong River basin in southwestern Vietnam (Fig. 1). The province is approximately 240 km from Ho Chi Minh City. It is situated south of the city of Can Tho, north of Soc Trang province, east of Kien Giang and Bac Lieu provinces and west of Vinh Long province. There are nine administrative units (five districts, two towns, and a central city) composing the province, occupying over 1602 km², equal 4% of the total area of the lower Mekong River basin in Vietnam. The studied area has a relatively flat surface with an average altitude of less than 2.5 m above sea level. It also has an intertwined hydrologic system (rivers plus canals), spanning 2300 km in length and a waterway density of 1.5 km/km².

Experimental Factors

There are three main pollution sources, polluting the hydrological systems of the studied area, including agricultural, industrial, and residential sources. Three zones located on or surrounding the pollution sources (residential areas = zone I, agricultural areas = zone II, and industrial zones = zone III) were selected to take surface water samples during the rainy and dry seasons for the current study. The residential areas had

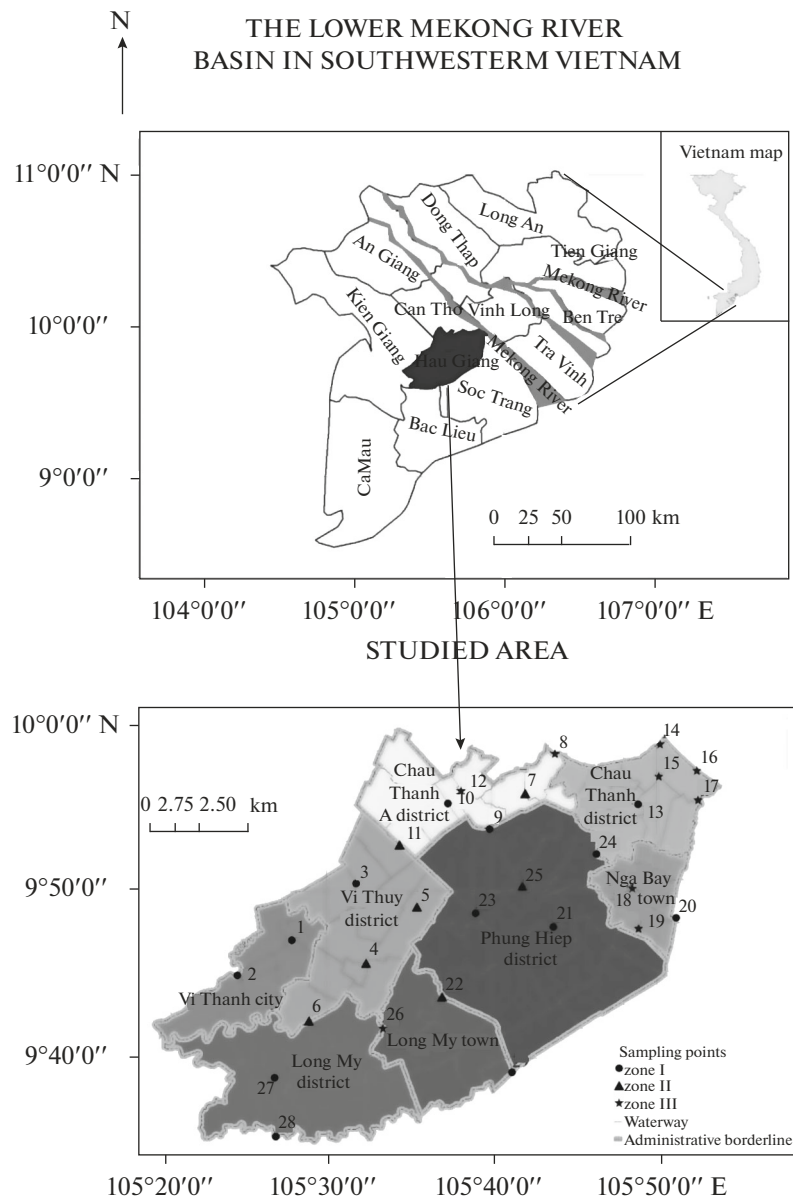


Fig. 1. The studied area and sampling points.

relatively high population densities and the canals or rivers selected for sampling were surrounded by residential households or communities on both sides. Residents have been living in these areas for many years, and domestic wastewater is discharged directly into the canals or rivers after passing through a septic system already built-in individual households. Because there was almost no centralized wastewater treatment system to treat home sewage, the discharged effluent varied in quality from site to site. The studied area is a rural province with a traditional and typical culture of agricultural production in the Lower Mekong River basin. Because the overall population density of the province is relatively low, there is plenty of rural areas reserved for agricultural production, typ-

ically paddy rice production. Annually, this studied area has two main rice seasons. Applications of chemical fertilizers and animal manure for intensive paddy rice production, coupled with strong surface runoff resulted from high and concentrated annual rainfall, may contaminate nearby surface water bodies. This is a different type of pollution from that of the residential areas. The province also encourages the development of industrial plants or parks that are obligated to treat wastewater before discharging to public canals or rivers. Therefore, the three pollution sources (agricultural, industrial, and residential sources) may differently affect surface water quality in Hau Giang province in the lower Mekong River basin.

The studied area has a tropical monsoon climate regime with two distinct seasons, the rainy season lasting from June to November and the dry season during the remaining months. Overall, the annual rainfall in the studied area was 1600–1800 mm, of which 85 to 95% occurred during the rainy months. In contrast, the studied area was short of water during the dry season, lowering surface water levels.

Water Sampling and Chemical Analysis

Twenty-nine points located on or surrounding the three experimental zones were selected to take surface water samples for this study (Fig. 1). There were thirteen points located within or close to zone I, seven close to zone II, and nine close to zone III. Surface water samples were collected from the pre-selected points in 2013, 2014, and 2015, in mid-March and mid-May (i.e., during the dry season) and in mid-August and mid-October (i.e., during the rainy season) of each year. In total, there were 348 water samples collected to analyze pH, dissolved oxygen (DO), total Fe, ammonium (NH_4^+), nitrate (NO_3^-), total suspended solids (TSS), phosphate (PO_4^{3-}), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and coliform bacteria (Coliform). In addition, surface water temperatures were measured in situ using a thermometer. The sampling method and chemical analyses of the collected water samples were conducted based on procedures recommended by the National Technical Regulation on surface water quality [23].

Statistical Methods

The current study can be considered as a completely randomized design with two factors and repeated observations but varying replicates. The two factors included pollution sources (residential, agricultural, and industrial sources) and seasons (dry and rainy seasons). Surface water samples were taken and measured four times a year for three years, meaning repeated observations occurred. Data were analyzed using Analysis of Variance (ANOVA), based on the experimental design and the following statistical analysis model:

$$y_{kij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \omega_{kij},$$

where y_{kij} is data from the k th water samples collected from the i th zone and in the j th season; μ is the overall mean; α_i is an effect due to the i th zone; β_j is an effect due to the j th season; $(\alpha\beta)_{ij}$ is the interactive effect of the two experimental factors; and ω_{kij} is a random error meeting the requirement of normal distribution and similar variance [18]. Each of the surface water quality parameters was examined for normal distribution and similar variance before conducting the ANOVA. When the ANOVA results indicated a signif-

icant difference at $P \leq 0.05$, Tukey's honest significant difference (HSD) test was used to identify significant interactive effects, otherwise main effects were tested. These statistical analyses were conducted using JPM 10 (SAS Institute Inc., North Carolina, USA). In addition, several multivariate techniques, including principal component analysis/factor analysis (PCA/FA) and discriminant analysis (DA), were conducted following the methods outlined in Phung, Huang [21], Vega, Pardo [34], and Singh, Malik [28]. In brief, PCA was conducted on individual pollution zones and the number of principal components with eigenvalues greater than 1 determined varimax factors for FA [1, 21]. Following the PCA, FA was conducted to eliminate the less-influential water quality parameters. Surface water quality parameters within individual varimax factors with loads greater than 0.5 were classified as relatively strong and thus were used for characterization of the studied zones [13]. DA was conducted using standard and stepwise methods to build discriminant functions, which were used to predict the classification of individual studied zones [22]. Multivariate techniques were implemented using IBM SPSS Statistics 23 (IBM Corporation, New York 10504-1722, USA). All figures reported from the current study were made using SigmaPlot 12 (Systat Software Inc., San Jose, California, USA).

RESULTS

Single Effects

The quality parameters of surface water that were not affected by the interaction of the pollution source (human impact) and season are shown in Figs. 2 and 3. Of the eleven investigated parameters reflecting surface water quality of the studied area, coliform bacteria were not significantly different among the three investigated zones or between two seasons, and thus its results were not shown. Other parameters, such as pH, NH_4^+ , PO_4^{3-} , and temperature, were significantly affected by seasons. The dry season had significantly higher pH, NH_4^+ , PO_4^{3-} , and temperature than the rainy season (Fig. 2). The pH of surface water varied from 6.3 to 7.7 with a mean of 7.0 in the dry season and from 6.1 to 8.4 with a mean of 6.9 in the rainy season. Similarly, NH_4^+ varied from 0.1 to 1.3 with a mean of 0.5 mg L^{-1} in the dry season and from 0.1 to 1.0 with a mean of 0.4 mg L^{-1} in the rainy season. PO_4^{3-} varied from 0.07–0.9 with a mean of 0.4 mg L^{-1} in the dry season and from 0.09–1.44 mg L^{-1} with a mean of 0.3 mg L^{-1} in the rainy season. And temperature ranged from 26.4–30.6°C with a mean of 29.3°C in the dry season and from 25.9–30.7°C with a mean of 28.7°C in the rainy season.

Other water parameters, such as NO_3^- , DO, and total Fe were significantly affected by both experimen-

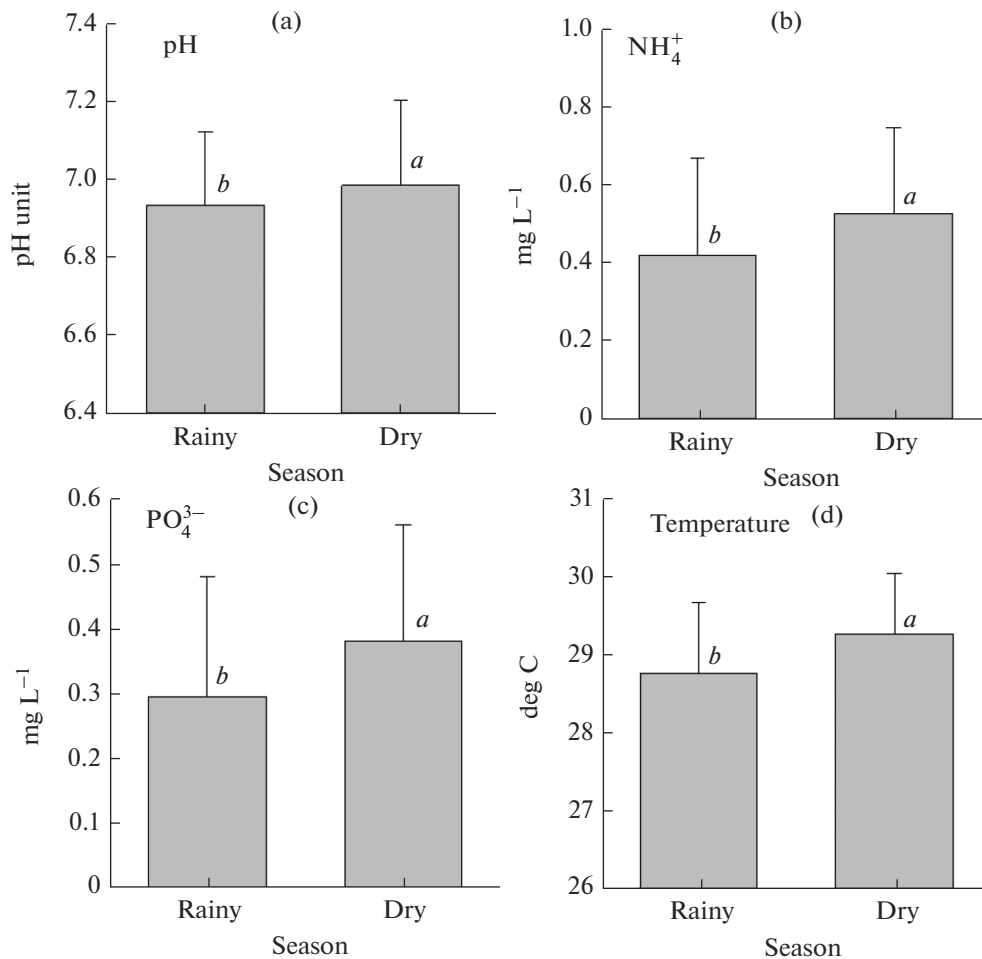


Fig. 2. The seasonal effect on pH, NH_4^+ , PO_4^{3-} , and temperature of surface water collected in the studied region. Error bars indicate the standard deviation of the mean. Bars attached with different letters are significantly different from the other.

tal factors but independently, meaning there was no interactive effect of the two investigated factors on these parameters (Fig. 3). The NO_3^- , DO, and Fe concentrations were significantly higher in the rainy season than in the dry season. NO_3^- varied from 1.1 to 3.5 with a mean of 2.0 mg L^{-1} in the rainy season and from 0.6 to 3.5 with a mean of 0.44 mg L^{-1} in the dry season. DO ranged from 3.2 to 5.7 with a mean of 4.2 mg L^{-1} in the rainy season and from 2.6 to 5.6 with a mean of 5.1 mg L^{-1} in the dry season. And Fe ranged from 0.7–3.8 with a mean of 1.8 mg L^{-1} in the rainy season and from 0.2–3.6 with a mean of 1.4 mg L^{-1} in the dry season. Additionally, the concentration of NO_3^- , DO, and total Fe was significantly affected by pollution sources (Fig. 3). NO_3^- was significantly higher in studied zones I and II, with means varying from 2.0 (zone I) to 2.1 mg L^{-1} (zone II) than in zone III with a mean of 1.8 mg L^{-1} . Similarly, the total Fe was significantly higher in zones I and II with the same mean of

1.63 than in zone III with a mean of 1.41 mg L^{-1} . In contrast, the DO was significantly higher in zone III with a mean of 4.45 than in zones I and II with means of 4.02 and 4.03 mg L^{-1} , respectively. The supplementary Tables 1, 2, 3 provided entire data used for the current study.

Interactive Effects

Surface water quality parameters, including BOD_5 , COD, and TSS, were significantly affected by an interaction of the seasons and pollution sources (Fig. 4). The BOD_5 and COD of surface water collected from zones I (12.7 and 20.0 mg L^{-1} , respectively) and III (12.0 and 18.9 mg L^{-1} , respectively) in the dry season were significantly higher than those collected in the rainy season (10.2, 17.6, 7.9, and 15.4 mg L^{-1} , respectively). However, the BOD_5 and COD collected from zone II in the dry season (9.9 and 16.6 mg L^{-1} , respectively) were not significantly different from those collected in the rainy season (9.6 and

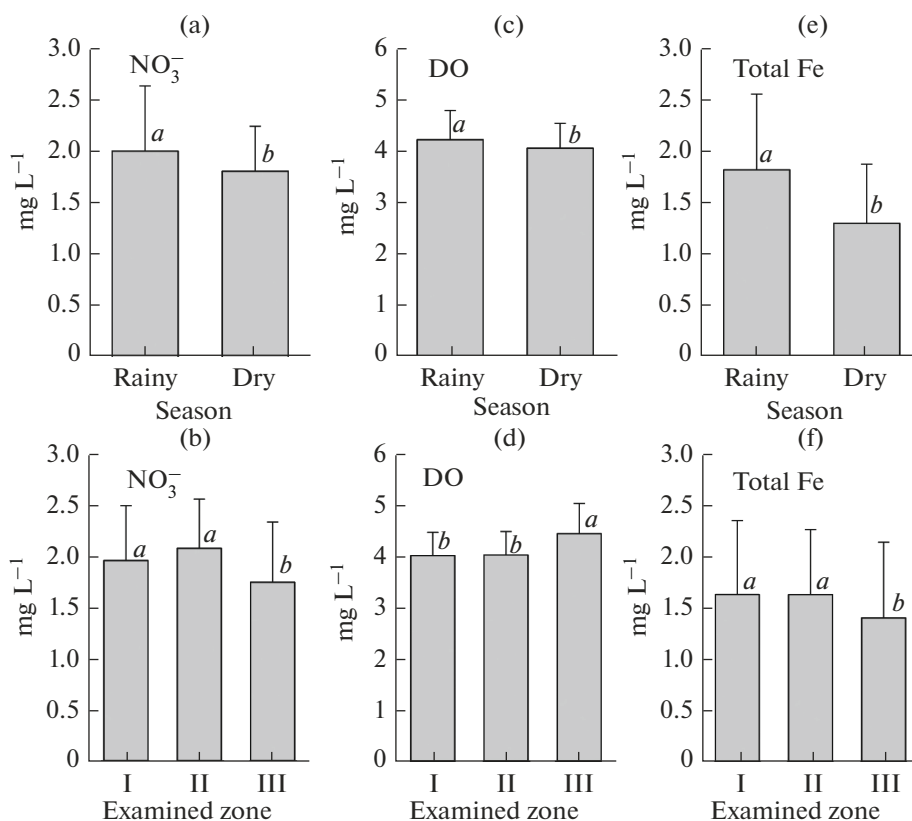


Fig. 3. Effects of season and pollution source on NO_3^- , DO, and total Fe of surface water in the studied region. Error bars indicate the standard deviation of the mean. Bars attached with the different letter are significantly different from the other.

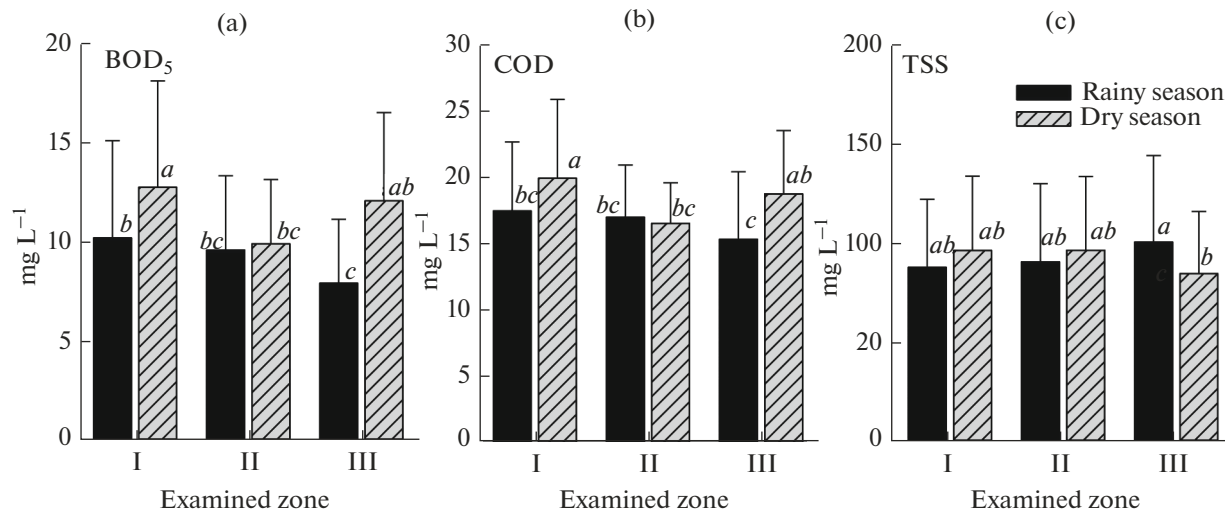


Fig. 4. Interactive effects of season and studied zone on BOD_5 , COD, and TSS of surface water. Error bars indicate the standard deviation of the mean. Bars attached with different letter are significantly different from each other.

17.1 mg L^{-1} , respectively). While TSS of surface water collected from zones I and II in the rainy season (88 and 90 mg L^{-1} , respectively) was not significantly different from that in the dry season (96 mg L^{-1} for both zones), the TSS from zone III in the rainy season (100 mg L^{-1}) was significantly higher than that in the dry season (85 mg L^{-1}).

Multivariate Analyses

PCA and FA were applied to identify latent factors and important surface water quality parameters representing individual pollution sources. The identified parameters can be used to characterize and compare the effective magnitude of the pollution sources in the three studies zones. Principal components (PC) from

Table 1. Loading values of 11 water quality parameters from Factor Analysis of three examined zones (VF: varimax factor). Bold numbers are those greater than 0.75, and underlined numbers are those greater than 0.5 and smaller than 0.75

Variables	Examined zone 1				Examined zone 2				Examined zone 3			
	VF 1	VF 2	VF 3	VF 4	VF 1	VF 2	VF 3	VF 4	VF 1	VF 2	VF 3	VF 4
pH	0.13	-0.16	0.11	<u>0.70</u>	0.22	0.08	0.14	0.84	-0.13	-0.13	<u>0.73</u>	-0.16
Temp	-0.06	0.23	-0.17	<u>0.62</u>	-0.18	-0.10	0.78	0.09	-0.06	0.07	-0.12	0.79
DO	-0.04	-0.11	<u>-0.73</u>	0.23	0.14	<u>-0.74</u>	-0.07	-0.09	<u>-0.51</u>	-0.43	-0.10	-0.17
Fe	-0.23	<u>0.69</u>	0.23	-0.22	0.14	0.60	0.18	<u>-0.50</u>	0.84	-0.13	-0.01	0.04
NH ₄ ⁺	-0.16	0.09	<u>0.74</u>	0.26	-0.15	0.23	<u>0.67</u>	0.06	<u>0.70</u>	0.12	-0.23	0.19
NO ₃ ⁻	0.21	<u>0.79</u>	0.07	0.02	<u>0.72</u>	0.22	0.05	-0.36	<u>0.74</u>	-0.11	0.31	0.09
TSS	-0.16	<u>0.62</u>	0.24	0.28	0.21	0.07	<u>0.67</u>	<u>-0.52</u>	<u>0.74</u>	-0.23	-0.28	-0.12
PO ₄ ³⁻	<u>0.56</u>	-0.09	0.12	0.30	<u>0.63</u>	0.00	-0.16	0.00	0.06	0.33	<u>0.74</u>	0.11
BOD ₅	0.88	0.04	0.06	-0.13	<u>0.67</u>	-0.01	-0.08	0.26	-0.07	0.86	-0.14	-0.08
COD	0.87	-0.03	-0.24	0.00	<u>0.68</u>	-0.53	-0.04	0.20	-0.16	0.84	0.26	0.02
Coliform	0.06	0.37	<u>0.62</u>	-0.02	0.11	<u>0.73</u>	0.00	0.00	0.21	-0.08	0.06	<u>0.62</u>
Percent	18	16	15	11	18	17	15	13	24	17	13	10
Cum Percent	18	34	50	61	18	35	50	63	24	41	54	64

Table 2. Classification functions coefficients derived from discriminant analysis of examined zones in the study area

Parameters	Standard method			Stepwise method		
	zone 1	zone 2	zone 3	zone 1	zone 2	zone 3
pH	226.6	227.1	224.2	211.2	212.2	209.3
Temp	36.2	36.2	36.2			
DO	3.4	3.2	4.9	-1.3	-1.4	0.2
Fe	16.7	16.3	16.0			
NH ₄ ⁺	-4.7	-6.6	-5.1			
NO ₃ ⁻	-1.3	-0.8	-1.3			
TSS	0.0	0.0	0.0			
PO ₄ ³⁻	10.8	11.9	10.9			
BOD ₅	2.8	2.9	2.8			
COD	-2.1	-2.2	-2.1	-0.3	-0.4	-0.3
Coliform	0.0	0.0	0.0			
Constant	-1329	-1330	-1318	-729.0	-734.4	-722.0

PCA, having eigenvalues greater than one, were considered significant and were used to determine varimax factors for FA. As a result, the first four PCs were retained based on their eigenvalues, and these PCs cumulatively explained 61, 63, and 64% of the total variance of surface water quality for zones I, II and III, respectively (Table 1). Four varimax factors (VF) representing the important PCs of individual studied zones, with loadings of eleven surface water parameters within individual varimax factors, are shown in Table 1. VF1 was the most important latent factor, and

it explained 18, 18, and 24% of the total variance of surface water quality of studied zones I, II, and III, respectively. The second most important latent factor was VF2, which explained 16, 17, and 17%. The third most important factor explained 15, 15, and 13%; and the least important factor explained 11, 13, and 10% of the total variance of zones I, II, and III, respectively. According to Liu, Lin [13], parameters with loading values greater than 0.75 can be considered as “strong,” those with values between 0.5 to 0.75 as “moderate,” and those with values between 0.3 to 0.5 as “weak.”

Table 3. A classification matrix from discriminant analysis of examined zones

Examined zone	% correct	Examined zone			Total
		1	2	3	
Standard method					
1	82	69	10	5	84
2	27	25	12	7	44
3	48	23	8	29	60
Total	59	117	30	41	188
Stepwise method					
1	65	55	23	6	84
2	41	22	18	4	44
3	45	25	8	27	60
Total	53	102	49	37	188

For zone 1, VF1 identified two parameters, BOD₅ and COD, with strong loading values higher than 0.75 and one parameters, PO₄³⁻, with a moderate loading value of 0.56. Similarly, zone II had four analyzed parameters, BOD₅, COD, PO₄³⁻, and NO₃⁻, with moderate VF1 loadings of, 0.67, 0.68, 0.63, and 0.72, respectively. Finally, zone III had five parameters with moderate to strong VF1 loading values, including TSS, NO₃⁻, NH₄⁺, Fe, and DO (Table 1).

Further assessment of surface water quality parameters of the three studied zones was conducted using DA, a statistical technique applied to build a model which characterized, predicted classification, and could be used to separate the three studied zones in the current study. DA was conducted on raw data after they were separated into three studied zones. There were two methods used for the DA, a standard method incorporating all parameters together and a stepwise method that eliminated the less-influential parameters from the final predictive model for each of three studied zones (Tables 2 and 3). The classification function coefficients for coliform bacteria and TSS were zero, while that of pH was highest in both methods. There were nine classification function coefficients associated with nine analyzed water parameters (except for Coliform and TSS) included in the predictive function of each of the three zones when the standard method was used. However, only three parameters, pH, DO, and COD were incorporated into the predictive functions when the stepwise method was used. The standard method resulted in an accurate prediction rate of 59%, while the stepwise method (using only 3 parameters) resulted in an accurate prediction rate of 53% (Table 3).

DISCUSSION

Characteristics of Pollution Sources

The water for the current study could be affected by both natural processes and anthropogenic activities. While natural processes, such as precipitation [7, 28], could induce relatively equal impacts across the studied area, the anthropogenic impacts, such as residential, agricultural, and industrial activities, may vary across the studied area, depending on magnitude and location. Table 1 shows that surface water quality in residential (zone I) and agricultural (zone II) zones were characterized by BOD₅, COD, and PO₄³⁻ (zone I) and by BOD₅, COD, PO₄³⁻, and NO₃⁻ (zone II), which had strong loadings associated with the most important varimax factor (VF1). In contrast, the industrial zone was identified through TSS, NO₃⁻, NH₄⁺, Fe, and DO. These indicated that VF1s of zones I and II could be considered as organic latent factors, while that of zone III could be as an inorganic latent factor. This difference may reflect the fact that zones I and II were selected from sites close to residential centers and communities and agricultural areas, respectively. Surface water of the two zones may be polluted with wastewater rich in organic matter. Sewage discharged from residential areas (domestic wastewater) was mainly composed of flows from bathrooms, kitchens, and toilets, characterized by high organic matter content and phosphorous compounds [6]. Through the use of principal component analysis and factor analysis, Simeonov, Stratis [27] attributed the organic latent factor to municipal effluents. Municipal wastewater was also concluded to be the main source of organic matter for river water [34].

Meanwhile, crop production in the agricultural zone may add pollutants to surface water through runoff or erosion from crop fields. Runoff caused by rainfall may carry natural (organic matter and soil sediment) and anthropogenic (animal manure and fertilizers) pollutants from agricultural fields and deposit them into the river or canal systems, which were sampled for the current study. The runoff effects on surface water quality were identified by Phung, Huang [21] from a study in a neighboring province. The authors used multivariate statistic methods, including cluster analysis, discriminate analysis, and factor analysis, to identify potential causes of surface water pollution. In contrast, the current study identified and separated the pollution sources before taking water samples. Soil manipulation, such as plowing, harrowing, and dibbling, was used to cultivate crops in the studied area. These practices break up and loosen soil particles, which can then be easily transported to rivers or canals as runoff. Surface water polluted with sediments rich in nutrients and organic matter were indicative of sites with agricultural runoff [9, 17]. Other sources of organic pollution in agricultural zones include decomposed rice residues, such as rice husk,

straw, and stubble left on fields, a known poor management habit of some farmers [16], leading to subsequent leaching of decomposed substances into rivers or canals.

The properties of effluents discharged from industrial parks should vary greatly with the type of industrial plants, such as chemical, textile, and food processing [29]. Nevertheless, principal component analysis and factor analysis of zone 3 showed that inorganic nutrients, such as TSS, NO_3^- , NH_4^+ , Fe, and DO, were most important in characterizing surface water quality of the zone. The zone was in areas close to industrial parks and manufacturing plants. These industrial plants should apply wastewater treatment technology that removes some organic matter before discharging it into the surface water system. Consequently, water collected from this zone had higher loadings with inorganic elements than organic elements.

Pollution Mechanisms Single Effects

There are two distinct seasons in the lower Mekong River basin, one of which is the rainy season that occurs from June to November and contributes approximately 90% of the total annual rainfall. The other is the dry season that occurs during the remaining months [35]. The rainy season added more water to the studied area, resulting in the frequent exchange of surface water in the sampled canals and rivers with water bodies from the outside area. In contrast, the dry season has low rainfall, so water in sampled canals and rivers less frequently flowed out of the studied area. In brief, the rainy season raised the surface water level of the studied area and increased the water exchange rate with outside water bodies, whereas the water level was lower during the dry season, limiting water exchange with external water bodies. These hydrologic regimes may influence water quality through (1) dilution effects and (2) washout effects during the rainy season, lowering pollutant concentration during the rainy season. Ozaki, Co [19] found that high tides resulted in greater surface water quality than low tides, indicating dilution and/or wash-out effects. Moreover, Bartram and Ballance [2] introduced the concept of residence time, which was the ratio of total volume to outflow rate, to explain higher water quality in water bodies with short residence times and lower water quality in water bodies with long residence times. This concept is highly applicable to the current study, as our sampling points had a shorter residence time in the rainy season due to a high water exchange rate than in the dry season. This is reflected through the Fig. 2, which showed that the concentrations of NH_4^+ and PO_4^{3-} in the rainy season were significantly lower than those in the dry season.

Highly concentrated rainfall during the rainy season may also induce intensive water runoff, bringing

agricultural additives, such as nitrogen fertilizers, to sampled rivers and canals. Nitrate formation from the decomposition of the nitrogen fertilizer runoff [36]

might explain higher NO_3^- concentrations in the rainy season than those in the dry season (Fig. 3a), particularly in the agricultural zone (Fig. 3b). The result from Fig. 3b was also in agreement with the conclusion of Tong and Chen [31] which stated that the nitrogen concentration was much higher in agricultural and urban zones than in other zones. Additionally, the increase of nitrate concentrations in rivers and streams, caused by surface runoff of nitrogen fertilizers [36], could be consolidated by factor analysis, which showed that nitrate loading value in the most important VF1 of the agricultural zone 2 was highest of the eleven surface water quality parameters investigated (Table 1). Another consequence of agricultural runoff in the rainy season could be lower pH of surface water due to nitrification of the ammonia derived from leached N fertilizers, forming hydrogen cations by ammonia-oxidizing bacteria [30]. The nitrification process is facilitated by oxidative conditions, which could occur more frequently in the rainy season than in the dry season, as indicated through higher DO concentrations shown in Fig. 3c. Sulfuric acid in the surface water formed from leached acid sulfate soils when exposed to sunlight [14, 20] may also reduce surface water pH more in the rainy season than in the dry season.

DO is the oxygen dissolved in the surface water and its concentration was negatively correlated with organic contaminants (e.g., BOD) [3]. This aligns with the current observation that DO concentrations were higher in the rainy season than in the dry season (Fig. 3c), whereas BOD_5 was lower in the rainy season than in the dry season in zones I and III (Fig. 4a). Higher DO concentrations in the surface water in the rainy season may also indicate that rainwater contained more dissolved oxygen. DO concentrations were significantly higher in industrial zone 3 than in the other zones (Fig. 3d), indicating that the effluent discharged from the industrial park may have been well-treated and removed more organic matter than the wastewater discharged from agricultural and residential zones. The lowest total Fe in zone 3 (Fig. 3b) may also support the assumption of well-treated effluent from the industrial zone.

Interactive Effects

An interesting result of the current study was an interactive effect between pollution source and season (Fig. 4). The total amount of monthly discharged pollutants from residential and industrial zones was relatively constant, compared to that from the agricultural zone, in which the discharge amount was seasonally dependent [34]. Lower BOD_5 and COD concentrations in surface water during the rainy season, in both

residential and industrial zones (Fig. 4), might indicate the dilution effect or washout effect due to high rainwater during the rainy season. Similar concentrations of BOD₅ and COD in both seasons within the agricultural zone could be attributed to the combined effects of dilution and runoff. High rainfall during the rainy season introduces (1) dilution effects or washout effects, which may lower contaminant concentrations and (2) runoff effects from agricultural fields that may bring more organic contaminants to surface waters, raising the BOD₅ and COD levels in canal or river water. Normally, there are two major rice seasons in the studied area, one from May to September and the other from November to February. The effects of runoff on surface water quality from agricultural zones could be enhanced during the rainy season due to agricultural activities [37], which were not seen in zones I or II.

TSS is defined as floating particles larger than 2 microns, and can include inorganic materials (sediment, silt, and sand) and organic materials, such as plankton, algae and decomposed plant and animal residues. The rainy season may increase TSS concentration through runoff effects from agricultural fields, roads, or residential areas [25], while the dry season may concentrate suspended solids (concentrated effect) due to lower water input. In addition, the dry season has more standing water and higher concentrations of NH₄⁺ (Fig. 2b), resulting in lower DO concentrations (Fig. 3), and higher organic matter concentrations as shown in zones I and II (Fig. 4), due to eutrophication [11]. An insignificant difference in TSS concentrations between seasons in zones I and II (Fig. 4c) could be explained with a similar magnitude of the two mechanisms, the concentrated and runoff effects. This is in agreement with findings by Rossi, Fankhauser [25]. Meanwhile, zone III reacted differently from the other two zones. Runoff effect from roads and land surfaces of the industrial zone may be stronger than the concentrated effect, resulting in higher TSS during the rainy season.

Predictive Model

The current study preselected and pre-classified sampling points into three pollution zones, making it different from other studies that used cluster analysis to separate sites based on similarity in surface water quality [26, 33]. Therefore, the observed results should reflect field conditions of the three examined zones. The current study showed that predictive models from the discriminant analysis could accurately predict as much as 59% of cases using the standard method and 53% of cases using the stepwise method, lower than those reported by [5, 28]. In a study conducted in a nearby province, Phung, Huang [21] found a reduced predictive function composed of three water quality variables, including turbidity, COD, and NH₃, with a

correct prediction percentage slightly higher than that in the current study. Notably, COD is one of three surface water quality parameters incorporated into the reduced predictive function from DA, indicating its importance to surface water quality in the lower Mekong River basin in southwestern Vietnam.

CONCLUSIONS AND IMPLICATION

The quality parameters of surface water, including pH, NH₄⁺, PO₄⁻, and temperature, were significantly higher in the dry season than in the rainy season, while NO₃⁻, DO, and Fe were affected both by pollution sources, including residential areas, agricultural production, and industrial manufacturing, and seasonal variation. The two investigated factors were shown to interactively affect BOD₅, COD, and TSS concentrations of surface water. While surface water in industrial and residential zones had lower BOD₅ and COD concentrations in the rainy season than in dry season, the agricultural zone had similar BOD₅ and COD concentrations in both seasons. TSS was not significantly different between the two seasons in residential and agricultural zones but was higher in the rainy season than in the dry season in the industrial zone. Overall mechanisms controlling these differences could be related to (1) direct effects of discharged effluents from pollution sources, (2) dilution or concentrated effects cause by season variation, and (3) runoff/leaching effects from agricultural fields, roads, and land surfaces. Multivariate analysis showed that three parameters, including pH, COD, and DO, could represent the 11 investigated parameters in predicting pollution sources of surface water. In conclusion, pollution sources directly affected surface water quality, while seasonal variation introduced indirect effects (dilution or runoff) to modify the effects of pollution sources. It is, therefore, necessary to appropriately manage local activities, including urbanization, agricultural production, and industrial manufacturing, to improve the surface water quality of the studied area and nearby provinces in the lower Mekong River basin in southwestern Vietnam.

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