

Seasonal Assessment of Ecological and Human Health Risks of Trace Metals in the Saigon River Surface Water, Vietnam

Binh Thanh Nguyen, Nghia Van Nguyen,* and Nam Van Thai

River water pollution with potentially toxic elements can be quantified via hydrological studies, while its potential impacts on the ecosystem and human health can be assessed via the indices of ecological risk (RI) and human health hazard (HI). This study aims to assess potential ecological and human health risks of trace-element pollution of the Saigon River surface water, based on seasonal, position, and tidal changes. Surface water samples are taken during dry and rainy seasons and analyzed for Cu, Cr, Mn, Pb, Ni, and Zn. The trace-element concentrations are used to compute RI and HI. Of the six elements, Cu accounted for 87.7 and 12.5% of the total variance of RI and HI, respectively. The RI and HI values are strongly correlated and are higher in dry season than in rainy season. The HI value of >1 for children suggests that children's health may be sensitive to the adverse impacts of the current status of the trace-element pollution. Overall, the trace-element pollution of the river surface water is at a moderate ecological risk in dry season but at a low ecological risk in rainy season. The potentially hazardous elements can have detrimental impacts on children's health in both seasons.

surface water can be most vulnerable to potentially hazardous trace-metal pollution, because it may act as a special medium for TMs to reside in or move to other ecosystem compartments, such as sediments, biota, and humans. Trace metal surface-water pollution may directly adversely affect not only the ecosystem but also human health via direct consumption as drinking water and/or via the food chain/web, depending on TM concentrations. Some TMs may be essential at a low concentration but harmful to the ecosystems and human health at high concentrations.

Given the adverse impacts of TM water pollution on both ecosystem and human health, ecological and human-health risk assessments are necessary for effective and sustainable management of water resources. As a tool for assessing potential ecological impacts, a risk index (RI) was developed by Håkanson,^[9] based on the measured concentrations of metals and the

1. Introduction

Globally, river surface-water pollution due to potentially toxic elements or trace metals (TMs) is one of the most serious threats to the ecosystem and public health, given their bioaccumulation, biomagnification, and non-biodegradability.^[1–3] Annually, a large quantity of diverse TMs is discharged to different ecosystem compartments of rivers from different sources, such as anthropogenic activities^[4–6] and natural sources.^[6–8] Consequently, river

concepts of “abundance principle,” “sink-effect,” and “sensitivity factor.” This approach has been widely applied to assess TM sediment pollution^[10–12] but limitedly applied to TM surface-water pollution.^[13] Similarly, a hazard index (HI) was developed to evaluate the possible human health risk of potentially toxic elements in water.^[14,15] This method was first developed by the U.S. Environmental Protection Agency (EPA)^[16] in order to quantify both carcinogenic and non-carcinogenic risks of potentially toxic elements to children and adults via ingestion and dermal absorption.^[17–19] A common feature of the two indices is the utilization of the measured concentrations of TMs of interest for assessment. For a comprehensive plan to minimize the harmful impacts of TMs, combining the two indices is required to assess both ecological and human health risks but remains limitedly reported.

Various sources of TMs can pollute the surface water of a sea-connecting river, which can exhibit variation in response to natural factors, such as rainfall and tidal regime. Not only may high rainfall dilute TM water pollution, but it also transports TMs from their source to the river. Flood tide may return some TMs from the sea to the river, whereas ebb tide may lower the TM concentration in the river water via the out-of-river flow. These impacts on the TM pollution of the river water have been widely studied and documented in related literature.^[20–22] However, assessments of the potential impacts of spatiotemporal and tidal changes on the

B. T. Nguyen
Institute of Environmental Science, Engineering, and Management
Industrial University of Ho Chi Minh City
Ho Chi Minh City 71408, Vietnam

N. Van Nguyen
Faculty of Safety Engineering, School of Technology
Van Lang University
Ho Chi Minh City 72311, Vietnam
E-mail: nghia.nv@vlu.edu.vn

N. Van Thai
HUTECH Institute of Applied Sciences
HUTECH University
Ho Chi Minh City 72308, Vietnam

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/clean.202300042>

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ecological and human health risks of the TM pollution of the river surface water based on the indices of RI and HI remain limitedly reported.

As a result, the present study was conducted on the Saigon River in Ho Chi Minh City in southern Vietnam. Flowing through the city, the river daily receives a considerable volume of discharged wastewater and solid wastes from industrial zones, residential regions, and agricultural areas.^[23,24] The river sediment and surface water have been polluted with TMs.^[23,25–28] The previous studies reported that the TM status of the river surface water is highly influenced by seasonal and spatial changes, which warrants further studies about the dependency of the ecological and human health risks of the TM surface-water pollution on the spatiotemporal changes. Therefore, this study sought to evaluate the potential ecological and human health risks of the TM pollution of the river surface water based on seasonal, spatial, and tidal changes. In the present study, it was hypothesized that 1) the dry season causes higher RI and HI values than does the rainy season; 2) the RI and HI values are significantly positively correlated with one another; and 3) the lower reaches of the river show higher RI and HI values than do the upper reaches.

2. Experimental Section

2.1. The Study Area

The present study was conducted on the Saigon River in Ho Chi Minh City. The river has a total length of ≈ 250 km and a catchment area of 4717 km^2 ^[29] and flows through Ho Chi Minh City before entering the Dong Nai River (Figure 1). More information about the study area, the river and Ho Chi Minh City, can be found in previously published studies.^[25,30,31]

2.2. Experimental Design, Water Sampling, and Chemical Analysis

The present study focuses on the following three main factors potentially contributing to TM surface-water pollution and associated ecological and human health risks: 1) rainy and dry seasons, 2) flood and ebb tidal stages, and 3) spatial dynamics of the river. A total of four sampling campaigns were implemented in the rainy season of 2018 (two campaigns) and in the dry season of 2019 (two further campaigns) to collect surface water samples from the lower reaches of the Saigon River. In each of the four campaigns, water samples were taken from the same 13 sites. To examine the tidal impacts, one sampling campaign during the flood tide and one during the ebb tide were undertaken for each season.^[25] Of the 13 sampling sites, from sites 2–12, two composite water samples per site were taken at the confluence of the main flow and its main tributary, with one on the main flow and the other at the mouth (70–150 m from the River) of its tributary. For sites 1 and 13, one water sample per site was taken to compare the TM concentrations of the river inflow and outflow water. Therefore, 24 surface water samples (two for sites 1 and 13, and 22 for sites 2–12) were taken in one sampling campaign, with a total of 96 samples for the four campaigns. Surface water samples were collected from a water depth of 0–50 cm of these

pre-planned sampling sites via a Van Dorn water sampler. For one water sample, a total of eight replicated samples were taken from the two sides of the River or mouth of its tributary into a 40-L bucket, and ≈ 5 L of water from this bucket was collected into a capped plastic bottle, which was immediately stored in an ice-box at 4°C and transported to a laboratory for analyses.

Surface water samples were analyzed for the six trace elements, copper (Cu), chrome (Cr), manganese (Mn), lead (Pb), nickel (Ni), and zinc (Zn), following the method by Giri and Singh.^[32] The water samples were filtered through a Whatman No.42 filter paper and acidified with concentrated nitric acid before analysis using an inductively coupled plasma-optical emission spectrometry (ICP-OES). The concentrations of the six TMs were calculated based on a standard curve with a coefficient of determination (r^2) value of >0.98 , formed from six standard solutions of the examined TMs. The accuracy and precision of the analysis results were checked by re-analyzing pre-known standard solutions for every 15 samples.

2.3. Assessment Methods

Overall, the method used to assess the ecological risk of the TMs in the surface water was comparable to that developed by Håkanson,^[9] which was applied to surface water by Zaccheaus et al.^[13] The method consisted of three steps for computing three factors. First, the contamination factor was estimated as follows^[33]

$$C_f^i = \frac{c_f^i}{c_{\text{ref}}^i} \quad (1)$$

where C_f^i is the contamination factor; c_f^i is the measured concentration (mg Li^{-1}) of element i in water; and c_{ref}^i is the background concentration (mg L^{-1}) of element i . For the present study, the c_{ref}^i values of all the six TMs are shown in Table 1 and were taken from a previous study about the Saigon River and Dau Tieng reservoir,^[34] which supplies water to the river. The water sample was evaluated to be of low contamination if the C_f^i value is <1 ; moderate contamination if $1 \leq C_f^i < 3$; considerable contamination if $3 \leq C_f^i < 6$; and very high contamination if the C_f^i value is ≥ 6 .^[33] Second, the ecological risk factor was calculated as follows

$$E_r^i = T_r^i \times C_f^i \quad (2)$$

where E_r^i is the ecological risk factor of element i ; and T_r^i is the “toxic response” factor of the element i . The values of T_r^i are presented in Table 1.^[9,35] The water risk assessment thresholds for E_r^i were based on the study by Ma and Han^[33] and are as follows: if $E_r^i < 40$; $40 \leq E_r^i < 80$; $80 \leq E_r^i < 160$; $160 \leq E_r^i \leq 320$; and $E_r^i > 320$, then the water sample is classified as low, moderate, considerable, high, and very high for ecological risk, respectively. Finally, the potential ecological risk index (RI) was computed as follows

$$\text{RI} = \sum_{i=1}^n E_r^i \quad (3)$$

Water samples with values of $\text{RI} < 150$; $150 \leq \text{RI} < 300$; $300 \leq \text{RI} \leq 600$; and $\text{RI} > 600$ were classified as low, moderate, considerable, and very high for potential ecological risk, respectively.^[9]

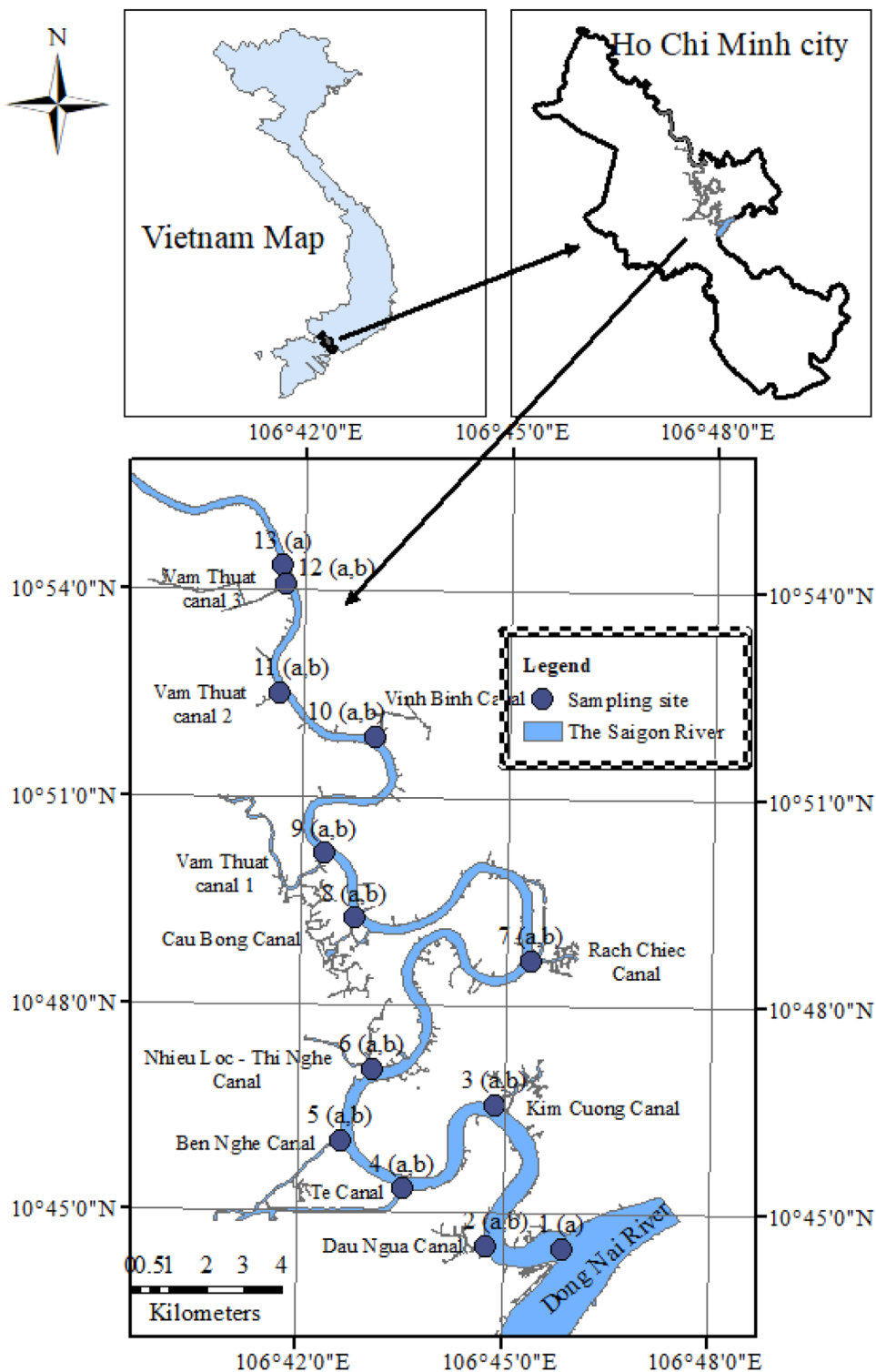


Figure 1. Map of the Saigon River in Ho Chi Minh City, Vietnam, with 13 sampling sites. a) Samples on the mainstream of the river, and b) samples on the mouth of the tributary canals. This map was created with ArcGIS 10.7 (ESRI, Redlands, California, USA).

Table 1. Background concentration (c_{ref}^i), toxic response factor (T_{ref}^i), and reference dose (R_{fd}) of six trace elements used for risk assessment.

Element	Ecological risk assessment			Human health risk assessment	
	c_{ref}^i [mg L ⁻¹]	Reference	T_{ref}^i Reference	R_{fd} [mg kg ⁻¹ day ⁻¹]	Reference
Cu	0.0007	[34]	5	[35]	0.005 [54]
Cr	0.03		2		0.003
Mn	0.015		1		0.14
Pb	0.01		5		0.0035 [19]
Ni	0.01		5		0.02 [55]
Zn	0.05		1		0.3 [54]

For human health risk assessment, this study followed the method by the EPA^[16] to calculate the non-carcinogenic risk associated with ingestion for both children and adults, which was also used in previous studies.^[17–19] The method first involved the calculation of the estimated daily intake (EDI) for both children and adults as follows

$$EDI = \frac{C_w \times IR \times EF \times ED}{B_w \times AT} \quad (4)$$

where EDI is the estimated daily intake of an element; C_w (mg L⁻¹) is the measured concentration of an element in water; IR is the ingestion rate (assuming 3 L day⁻¹ for adults and 1 L day⁻¹ for children);^[36] ED is the exposure duration (18 and 52 years for children and adults, respectively); B_w is the body weight (10 and 55 kg for children and adults, respectively); and AT is the averaging time (6570 and 18 980 days for children and adults, respectively). The hazard quotient (HQ) for non-carcinogenic risk assessment was derived from Equation (5).

$$HQ = \frac{EDI}{R_{fd}} \quad (5)$$

where R_{fd} is the reference dose (mg L⁻¹) of a trace element, the maximum acceptable dose causing no harmful effect on the individual if exposed to this level for a long time. The R_{fd} values for the six TMs are given in Table 1. The final step for human health risk assessment was to compute the hazard index (HI) as follows

$$HI = \sum_{i=1}^n HQ_i \quad (6)$$

where n is the number of the TMs under assessment. If HI or HQ was <1, the non-carcinogenic adverse effect of the TMs was assumed to be negligible.

2.4. Statistical Analyses

Hierarchical cluster analysis^[37] was applied to group the 13 sampling sites into high and low-risk classes based on the RI and HI values of the 96 samples. Multiple regression analysis was performed to quantify the relative importance of the individual

potential predictors that contributed to the total variance of the RI and HI values. A simple linear regression analysis was conducted to describe the relationship between the RI and HI values. A three-way analysis of variance (ANOVA) was performed to compare the means of the experimental factors (season, spatial river position, and tidal stage). A full statistical ANOVA model was implemented as follows

$$\gamma_{ijk} = \mu + \beta_i + \alpha_j + \alpha\beta_{ij} + \tau_e + \beta\tau_{ie} + \alpha\tau_{je} + \alpha\beta\tau_{ije} + \varepsilon_{ijk} \quad (7)$$

where γ_{ijk} is the response of the combination of three factors; μ is the overall mean; β_i is the fixed effect of the i th season; α_j is the fixed effect of the j th tide; $\alpha\beta_{ij}$ is the interaction effect of the season and tide; τ_e is the fixed effect of the e th river position; $\beta\tau_{ie}$ is the interactive effect of the season and river position; $\alpha\tau_{je}$ is the interaction effect of the tide and river position; $\alpha\beta\tau_{ije}$ is the interactive effect of the season, tide, and river position; and ε_{ijk} is the random error with a mean of zero under the normal distribution.^[38] The Tukey's honest significant difference (HSD) test following ANOVA was used to detect the significant mean differences between the treatment groups at a significance level (P) of ≤ 0.05 . The scatter plot was used to visualize the spatial variations of the measured indices and parameters. All statistical analyses were conducted using JMP Pro 16.0 (SAS Institute, NC, USA).

3. Results

3.1. Potential Ecological Risk

Of the six TMs examined, Mn had the highest mean concentration (0.114 mg L⁻¹) with a range of 0.007–0.245 mg L⁻¹, followed by Zn (mean = 0.022 mg L⁻¹), Cu (0.018 mg L⁻¹), Cr (0.014 mg L⁻¹), Pb (0.013 mg L⁻¹), and Ni (0.007 mg L⁻¹). The interrelationships among these elements are shown in Table S1, Supporting Information. Cu had the highest contamination factor (25.4), followed by Mn (7.6), Pb (1.3), Ni (0.7), Cr (0.5), and Zn (0.4) (Table 2). The dry season exhibited a significantly higher contamination factor for Mn, Pb, and Zn than did the rainy season, whereas the two seasons had a similar contamination factor for the other TMs. Likewise, the dry season had a higher ecological risk factor for Mn, Pb, and Zn than did the rainy season. Cu showed the maximum value of the ecological risk factor (127.1), followed by Mn (7.6), Pb (6.6), Ni (3.5), Cr (1.0), and Zn (0.4).

The potential ecological risk index was significantly higher in the dry season and flood tide (159), followed by the other combinations of dry season + ebb tide (156), rainy season + flood tide (136), and rainy season + ebb tide (133) (Figure 2a). Water quality in both tidal stages was at the moderate ecological risk (RI >150) in the dry season but at the low ecological risk in the rainy season. The RI values greatly varied with the sampling sites along the river, with the higher RI values occurring in the dry season than in the rainy season, regardless of the sampling site, except for site 5 (Figure 2b). In the dry season, sites 1, 2, and 6 exhibited the maximum RI values of 202, 195, and 206, respectively. In the rainy season, sites 1, 2, and 9 had the minimum RI values of 110, 126, and 112, respectively. All the sites in the dry season, except for sites 4 and 5, were at the low ecological risk, whereas all the

Table 2. Contamination factor and ecological risk factor of 6 tested trace elements of water samples collected in the two seasons and during two tides.

Season	Tidal stage	Cu	Cr	Mn	Pb	Ni	Zn
Contamination factor							
Rainy season	Ebb tide	23.43 (1.43)	0.46 (0.05)	6.11 ^b (0.63)	1.00 ^b (0.03)	0.66 (0.11)	0.31 ^b (0.07)
	Flood tide	24.25 (1.95)	0.53 (0.06)	4.86 ^b (0.8)	1.02 ^b (0.09)	0.72 (0.11)	0.32 ^b (0.04)
Dry season	Ebb tide	26.70 (2.01)	0.47 (0.06)	9.56 ^b (0.97)	1.61 ^a (0.01)	0.58 (0.09)	0.60 ^b (0.12)
	Flood tide	27.12 (1.85)	0.45 (0.05)	9.70 ^b (1.44)	1.66 ^a (0.07)	0.80 (0.12)	0.53 ^{a,b} (0.05)
Ecological risk factor							
Rainy season	Ebb tide	117.1 (7.2)	0.9 (0.1)	6.1 ^b (0.6)	5.0 ^b (0.1)	3.3 (0.5)	0.3 ^b (0.1)
	Flood tide	121.3 (9.8)	1.1 (0.1)	4.9 ^b (0.8)	5.1 ^b (0.5)	3.6 (0.5)	0.3 ^b (0)
Dry season	Ebb tide	133.5 (10.1)	0.9 (0.1)	9.6 ^a (1)	8.0 ^a (0.1)	2.9 (0.5)	0.6 ^a (0.1)
	Flood tide	135.6 (9.3)	0.9 (0.1)	9.7 ^a (1.4)	8.3 ^a (0.3)	4.0 (0.6)	0.5 ^{a,b} (0.1)

The numbers in parenthesis are the standard deviation of the mean. For the individual factor, within each of the columns, data attached with the same letter are not significantly different from the others.

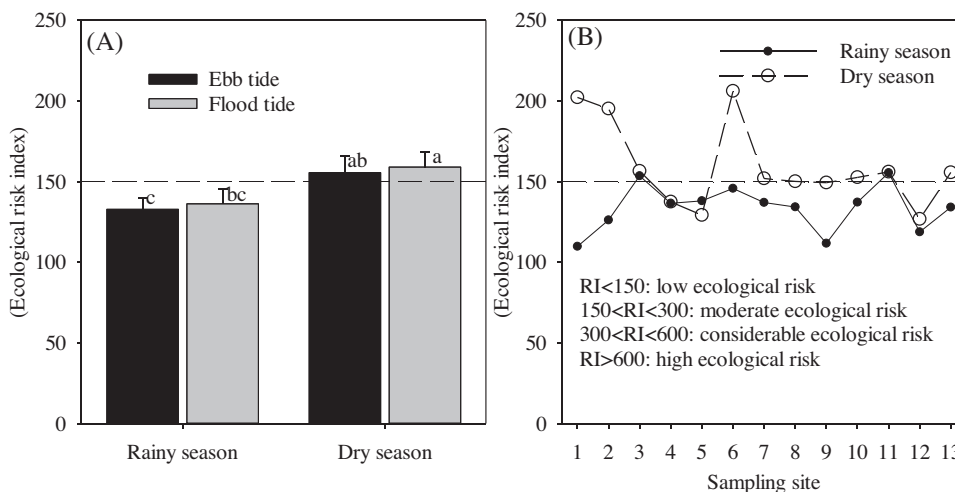


Figure 2. Ecological risk index (RI) a) of the surface water in two seasons and b) of 13 sampling sites. Within panel (a), bars with the same letter are not significantly different from the other. Error bars indicate standard errors.

sites in the rainy season, except for sites 3 and 11, were at the low ecological risk.

3.2. Potential Human Health Risk

Table 3 shows that the estimated daily intake (EDI) values of all six TMs were higher for children than for adults. Mn for children and adults resulted in the highest mean EDI values (11.4 and 6.2 g kg⁻¹ day⁻¹), followed by Zn (2.2 and 1.2 g kg⁻¹ day⁻¹), Cu (1.8 and 1.0 g kg⁻¹ day⁻¹), Cr (1.4 and 0.8 g kg⁻¹ day⁻¹), Pb

(1.3 and 0.7 g kg⁻¹ day⁻¹), and Ni (0.7 and 0.4 g kg⁻¹ day⁻¹), respectively. Whereas the tidal stage did not significantly affect the EDI values for children and adults, the season exerted a significant impact on the EDI values of Mn, Pb, and Zn, with a higher EDI value occurring in the dry season than in the rainy season.

Similar to the EDI value, the hazard quotient (HQ) values of all six TMs were higher for children than for adults (**Table 4**). On average, Cr had the maximum HQ values (0.48 and 0.26), followed by Pb (0.38 and 0.21), Cu (0.36 and 0.19), Mn (0.08 and 0.04), Ni (0.03 and 0.02), and Zn (0.007 and 0.004) for children and adults, respectively. The HQ values of Mn, Pb, and Zn were

Table 3. Estimated daily intake (EDI) ($\mu\text{g kg}^{-1} \text{ day}^{-1}$) of the children and adults for six examined trace elements in water samples collected in the two seasons and during two tidal stages.

Season	Tide stage	Cu	Cr	Mn	Pb	Ni	Zn
Children							
Rainy season	Ebb tide	1.64 (0.1)	1.38 (0.15)	9.17 ^b (0.94)	1.00 ^b (0.03)	0.66 (0.11)	1.55 ^b (0.34)
	Flood tide	1.70 (0.14)	1.60 (0.17)	7.29 ^b (1.2)	1.02 ^b (0.09)	0.72 (0.11)	1.60 ^b (0.19)
Dry season	Ebb tide	1.87 (0.14)	1.40 (0.17)	14.34 ^a (1.46)	1.61 ^a (0.01)	0.58 (0.09)	3.02 ^a (0.59)
	Flood tide	1.90 (0.13)	1.34 (0.16)	14.56 ^a (2.16)	1.66 ^a (0.07)	0.80 (0.12)	2.65 ^{a,b} (0.26)
Adults							
Rainy season	Ebb tide	0.89 (0.05)	0.75 (0.08)	5.00 ^b (0.51)	0.55 ^b (0.02)	0.36 (0.06)	0.85 ^b (0.19)
	Flood tide	0.93 (0.07)	0.87 (0.09)	3.98 ^b (0.65)	0.56 ^b (0.05)	0.39 (0.06)	0.87 ^b (0.1)
Dry season	Ebb tide	1.02 (0.08)	0.76 (0.09)	7.82 ^a (0.79)	0.88 ^a (0.01)	0.32 (0.05)	1.65 ^a (0.32)
	Flood tide	1.04 (0.07)	0.73 (0.09)	7.94 ^a (1.18)	0.90 ^a (0.04)	0.44 (0.07)	1.45 ^{a,b} (0.14)

The numbers in parenthesis are the standard deviation of the mean. For each of the children and adults, within each column, data attached with the same letter are not significantly different from the others.

Table 4. Hazard quotient (HQ) for the children and adults for six examined trace elements in water samples collected in the two seasons and during two tides.

Season	Tide stage	Cu	Cr	Mn	Pb	Ni	Zn
Children							
Rainy season	Ebb tide	0.33 (0.02)	0.46 (0.05)	0.07 ^b (0.007)	0.29 ^b (0.008)	0.033 (0.005)	0.005 ^b (0.001)
	Flood tide	0.34 (0.03)	0.53 (0.058)	0.05 ^b (0.009)	0.29 ^b (0.026)	0.036 (0.005)	0.005 ^b (0.001)
Dry season	Ebb tide	0.37 (0.03)	0.47 (0.057)	0.10 ^a (0.01)	0.46 ^a (0.003)	0.029 (0.005)	0.010 ^a (0.002)
	Flood tide	0.38 (0.03)	0.45 (0.053)	0.10 ^a (0.015)	0.47 ^a (0.019)	0.040 (0.006)	0.009 ^{a,b} (0.001)
Adults							
Rainy season	Ebb tide	0.18 (0.01)	0.25 (0.027)	0.04 ^b (0.004)	0.16 ^b (0.004)	0.018 (0.003)	0.003 ^b (0.001)
	Flood tide	0.19 (0.01)	0.29 (0.032)	0.03 ^b (0.005)	0.16 ^b (0.014)	0.020 (0.003)	0.003 ^b (0.002)
Dry season	Ebb tide	0.20 (0.02)	0.25 (0.031)	0.06 ^a (0.006)	0.25 ^a (0.002)	0.016 (0.003)	0.005 ^a (0.001)
	Flood tide	0.21 (0.01)	0.24 (0.029)	0.06 ^a (0.008)	0.26 ^a (0.011)	0.022 (0.003)	0.005 ^a (0.0005)

The numbers in parenthesis are the standard deviation of the mean. If $HQ > 1$ its non-carcinogenic effects are concerned, while $HQ < 1$, its effects are acceptable. For each of children and adults, within each of the columns data attached with the same letter are not significantly different from the others.

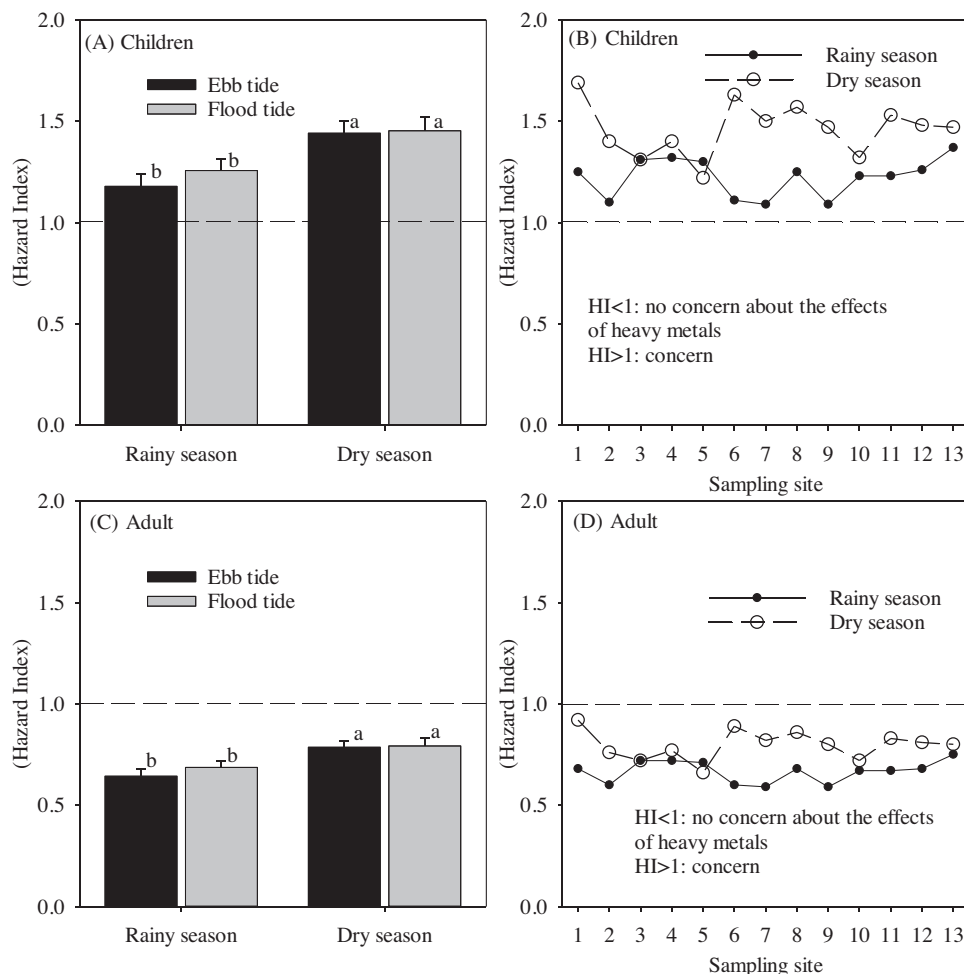


Figure 3. a,c) Hazard index (HI) of the surface water in two seasons and b,d) of 13 sampling sites. Within panels (a) and (b), bars with the same letter are not significantly different from the other. Error bars indicate standard errors.

substantially higher in the dry season than in the rainy season, whereas the HQ values did not significantly change between the two tidal stages for both children and adults. The HQ values of the TMs in the two seasons for children and adults were less than unity, a threshold to assess their non-carcinogenic effect.

The hazard index values for children and adults were considerably higher in the dry season than in the rainy season, with a higher HI value being for children (1.33) than for adults (0.73) (Figure 3). For children, the average HI value was 1.44 (1.18) and 1.45 (1.26) at the ebb and flood tides in the dry season (during the rainy season), respectively (Figure 3a). The HI values for children at all 13 sampling sites in the two seasons and two tidal phases were >1 (Figure 3b). For adults, the average HI value ranged from 0.66 in the rainy season to 0.79 in the dry season (Figure 3c). The HI values for adults in the two seasons and two tidal stages were <1 for all 13 sampling sites (Figure 3d).

3.3. Multivariate Analysis

For both children and adults, the two indices (RI and HI) were significantly positively correlated with each other, with an r^2 value

of 0.37 ($P < 0.05$) (Figure 4a,b). For every one-unit rise in the RI value, the HI value increased by 0.004 for children and by 0.002 for adults. The multiple regression analysis showed that the RI value was significantly associated with the concentrations of all the TMs, except for Zn (Table 5). Of the total variance of the RI value, Cu, Pb, Mn, Ni, and Cr, explained 88, 1.2, 0.5, 0.4, and 0.1%, respectively. The HI values of children and adults were strongly correlated with the concentrations of the TMs, of which Cr explained the highest percentage of the variance (57.5%), followed by Pb (16.8%), Cu (12.5%), Mn (2.4%), Ni (0.58%), and Zn (0.02%).

The 13 sampling sites were grouped into two clusters based on the HI and RI values (Figure 5). In the rainy season, sites 4, 5, 13, 8, 10, 3, and 11 were grouped into cluster 1, whereas the others were grouped into cluster 2 (Figure 5a). In the dry season, sites 2, 6, and 1 were assigned to cluster 1, with the others remaining in cluster 2 (Figure 5b). Regardless of the season, cluster 1 showed higher RI (141.3 in the rainy season and 201.2 in the dry season) and HI values (1.29 for children and 0.70 for adults in the rainy season and 1.57 for children and 0.86 for adults in the dry season) than cluster 2 (RI = 124.9 in the rainy season and 146.6 in the dry season and HI = 1.15 for children and 0.63 for adults in the

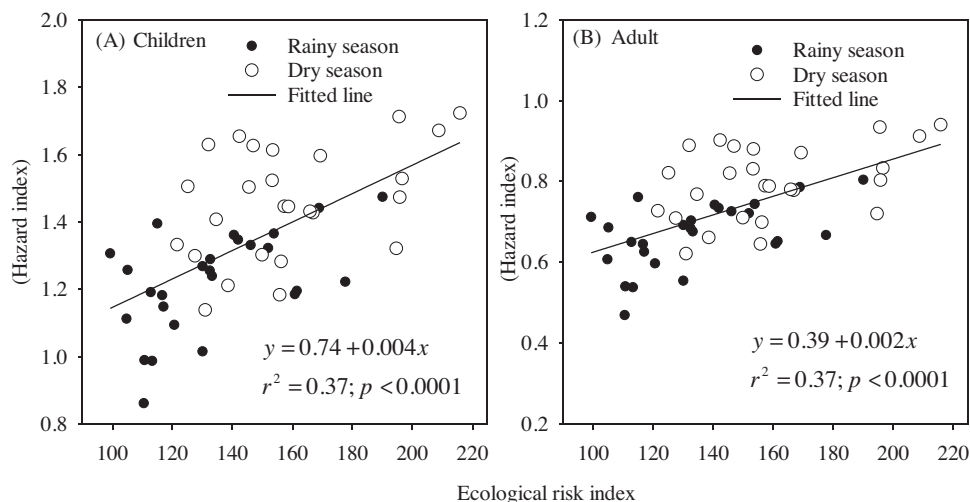


Figure 4. Relationship between the ecological risk index and human health hazard index for a) children and b) adult with a coefficient of determination (r^2) and associated probability (p) shown.

Table 5. Percentage of individual trace elements contributing to the total variance of ecological risk index (RI) and human health hazard index (HI) of the children and adults.

Factor	RI			HI (children)			HI (adults)		
	Estimate	Sum of squares	%	Estimate	Sum of squares	%	Estimate	Sum of squares	%
Cu	7034	93 631	87.7	19.5	0.7	12.5	10.7	0.2	12.5
Cr	138	56	0.1	33.7	3.3	57.5	18.4	1.0	57.5
Mn	66	1294	1.2	0.7	0.1	2.4	0.4	0.0	2.4
Pb	583	401	0.4	28.7	1.0	16.8	15.6	0.3	16.8
Ni	611	501	0.5	5.01	0.03	0.58	2.74	0.01	0.58
Zn	26	15	0.014	0.25	0.00	0.02	0.14	0.00	0.02
Error		10 885	10.2		0.6	10.2		0.2	10.2
Total variance		106 782	100.0		5.8	100.0		1.7	100.0

The bold numbers indicate the associated metal was not significant in explaining the total variance of the corresponding index.

rainy season and 1.43 for children and 0.78 for adults in the dry season) (Figure 5c,d). The mean values of the RI and HI values of both clusters were higher in the dry season compared to the rainy season.

4. Discussion

This study applied the general principle of the sedimentological approach by Håkanson^[9] to assess the potential ecological risk of the TM surface-water pollution. The key difference between them was the background level (c_{ref}^i), which was used to estimate the contamination factor. The background concentration employed in the present study for the water quality assessment was taken from a previous study by the Japan International Cooperation Agency JICA,^[34] which showed the original surface-water concentrations of the TMs of the Saigon River and Dau Tieng reservoir. The Saigon River water was mainly supplied by this reservoir water body, which can be used as a reference level for the ecological risk assessment. Many risk-assessment studies were carried

out by deriving background levels from previous studies in the local region^[39,40] or elsewhere.^[41]

The contamination factor of >6 for Cu and Mn that was averaged over the two seasons and two tidal stages (Table 2) pointed to the high Cu and Mn pollution of the Saigon River surface water.^[9,33] The examined elements were ranked in the following order: Mn (0.11 mg L⁻¹) > Zn (0.022 mg L⁻¹) > Cu (0.018 mg L⁻¹) > Cr (0.014 mg L⁻¹) > Pb (0.013 mg L⁻¹) > Ni (0.007 mg L⁻¹). The maximum contamination factor of Cu may be attributed to its lowest background level, relative to those of the others (Table 1). Pb also played an important role in the river surface-water pollution as its contamination factor for the two seasons was >1. The river surface water did not show significant levels of Cr, Ni, and Zn pollution. Based on the criteria by Håkanson,^[9] the river surface water was at the considerable ecological risk with Cu in both seasons (Table 2). The Saigon River surface water was neither potentially nor ecologically at risk in terms of the other TMs since their ecological risk factor values were <40.

The significantly higher RI value in the dry season than in the rainy season (Figure 2) confirmed our initial hypothesis. The

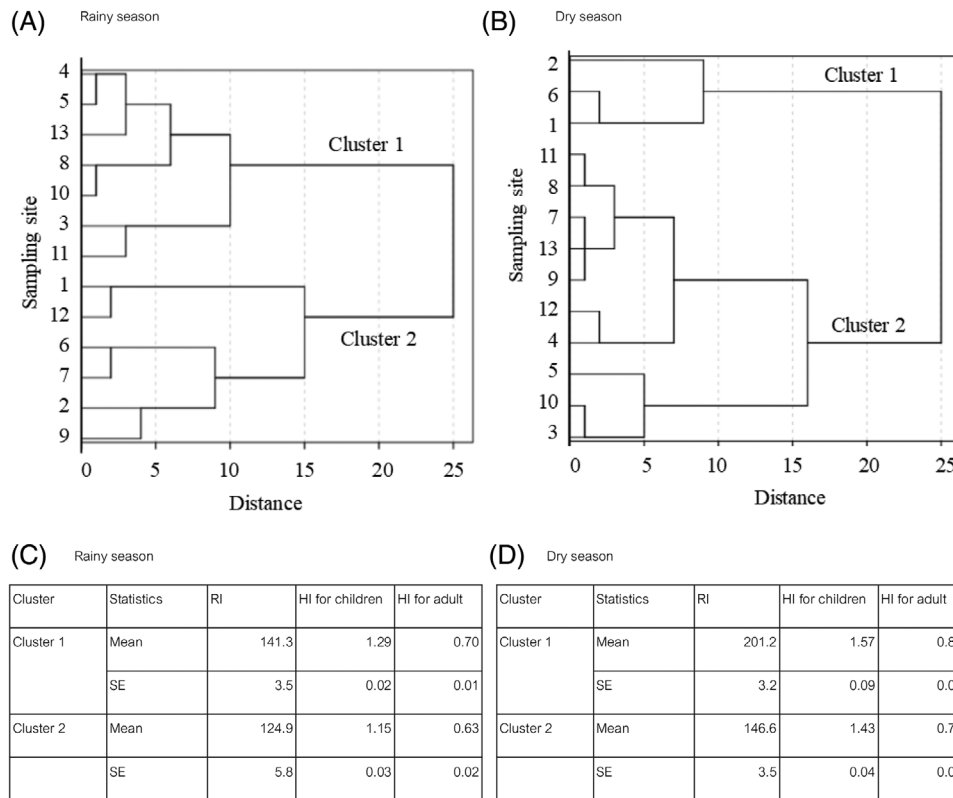


Figure 5. a,b) Cluster analysis for two seasons, and c,d) associated risk and hazard indexes, of the resultant clusters.

Saigon River surface water was at the moderate ecological risk of the TMs in the dry season according to the RI value of >150 but at the low ecological risk in the rainy season according to the RI value of <150 (Figure 2).^[9] The similar seasonal effect on the same River water pollution was previously reported in related literature.^[42,43] Nguyen et al.^[25] found that the dry season led to a significantly higher surface-water concentration of the TMs than did the rainy season, but the seasonal effect also depended on the tidal stage. Likewise, Li et al.^[44] reported that the TM concentrations in surface water of the junction of four rivers in Linyi City, China, were lower in the rainy months than in the dry months, due to the pollutant-concentrating effect of the dry period and the dilution effect of the rainy period. The higher contamination factor and ecological risk factor in the dry season than in the rainy season (Table 2) resulted in a greater RI value in the dry season than in the rainy season.

The HQ values of <1 for the individual TMs in the present study were similar to those of a previous study on the same river.^[45] The average HI value of >1 for children suggested that adverse impacts on children's health from exposure to the river water are conceivable. Because children are more vulnerable to the adverse health effects of metal pollution than adults,^[46,47] children should be paid special attention when the health risk of the TM pollution of the river surface water is minimized. On a per-body-weight basis, children were projected to intake more metals from the river water than adults, based on the EDI values (Table 3), which is due to the lower weight of children than adults. This led to a higher HI value for children than for adults (Figure 3), which was in line with previous studies.^[15,48]

Similar to the RI value, the higher HI value of the surface water in the dry season than in the rainy season (Figure 3) indicated more water pollution in the dry season than in the rainy season. The higher HI values of sites 1, 6, 8, and 11 compared to the others in the dry season suggested that these sites could be affected by the point sources of the TM pollution. Located in the estuary, site 1 may be adversely affected by the activities of boats and cargo ships, which may disturb the metal-containing sediment at the bottom of the river.^[25] Located inside Ho Chi Minh City, sites 6, 8, and 11 could be adversely affected by discharged effluents, wastewater, or solid wastes from various sources, such as residential and industrial areas. Anthropogenic activities along the river banks and inside Ho Chi Minh City were recognized as one of the main sources of the TM pollution of the river surface water.^[23] Increased water consumption for residential, industrial, and agricultural activities in Ho Chi Minh City may increase the TM pollution level of the Saigon River surface water,^[49] which warrants future studies.

The three main factors appeared to contribute to the increasing risks of environmental and public health due to the TM contamination of the Saigon River surface water. First, the seasonal variations appeared to influence the hydrological processes of the river. In the rainy season, more inflow water from the upper catchment or from Ho Chi Minh City to the sea through the river may cause a dilution effect (lowering of pollutant concentrations) and washout effect (cleaning of pollution sources).^[25] In the dry season, less water was delivered to the river due to low rainfall, and the associated strong evaporation process may raise the TM concentrations of the surface water and further

concentrate the effects of the pollutants.^[44] This study appeared to evidence these relationships according to its results that all contamination factors, ecological risk factor (Table 2), EDI (Table 3), HQ (Table 4), RI (Figure 2), and HI (Figure 3) values were higher in the dry season than in the rainy season. Second, the pronounced spatial variation of the TM pollution could be driven by point sources along the river banks that released the TMs into the surface water. The two indices of RI and HI were spatially grouped into two clusters, where cluster 1 was higher than cluster 2 in terms of both indices (Figure 5). The activities of various boats and cargo ships in the lower reaches could be the primary cause of the surface water pollution of sites 1 and 2 in cluster 1 in the dry season. Site 6 was located at the meeting point of the Saigon River and the Thi Nghe-Nhieu Loc canal. Previously, the canal was reported to be polluted with polychlorinated biphenyl, an organic chlorine compound, and some potentially toxic elements.^[50]

The last one might be related to the TMs, which differed from one another in terms of their contamination factor and ecological risk factor (Table 2). Of the six TMs, Cu accounted for 87.7% of the total variance of the ecological risk index (Tables 1 and 5). The Cu concentration increased by 23–27 times since 2013,^[34] thus leading to its higher contamination factor (averaged over the two seasons and two tidal stages) compared to the others. Cu also elucidated $\approx 12.5\%$ of the HI variance for children and adults. Copper may be found in many ecosystem compartments as it can be released from various sources, such as mining, domestic wastewater, combustion of fossil fuels, wood production, native soil, decaying plants, and forest fires.^[51] Although Cu is an essential nutrient, prolonged exposure to excessive levels may cause headache, dizziness, nausea, diarrhea, liver and kidney damage, and even death.^[51] The Cr and Pb concentrations also influenced the HI values for children and adults (Table 5). The significant correlation of Pb with Zn and Mn (Table S1, Supporting Information) suggested that these three TMs could result from the same source. The three TMs might enter the Saigon River from industrial, agricultural, and residential activities inside Ho Chi Minh City.^[23,25]

While RI is widely used as a tool to assess ecological risk, HI is another tool to assess the human health risk of the TM surface-water pollution. The two indices were significantly correlated with each other with a coefficient of determination (r^2) of 0.37 (Figure 4), leaving 63% of the total variance unaccounted for. This suggests that the ecological risk assessment of the TM pollution of the river surface water could not be used in replacement of the human health risk. Nonetheless, the high ecological risk of ecosystem degradation may be used as an indicator of the potential human health risks.

The results provide important insights and implications. The basic concept of the sedimentological approach could be successfully applied to the potential ecological risk assessment of the TM pollution of the river surface water and can be generalized to other rivers worldwide. Despite many studies of the ecological risk assessment of TMs in river sediments,^[10,12,44] the spatiotemporal risk assessment in river surface water remains underrepresented. This study found that the ecological risk was higher in the dry season than in the rainy season, suggesting that the dilution effects of the rainy season played an important role in the risk reduction in the Saigon River surface-water pollution. The

present study showed a linear relationship between the ecological and human health risk indices ($r^2 = 37\%$). The relatively low r^2 value pointed to the two risk types as complementary but not as a replacement for one another. Last but not least, an implication for public health and environmental management was related to the higher risk of children's health to the potentially harmful elements. Environmental management strategies toward reducing metal water pollution should distinguish the public health risks in terms of children and adults and be planned and implemented accordingly for long-term development.

There are a few limitations that need to be addressed in the present study. First, the background concentrations of the TMs used for the assessment were from a previous study conducted in the upper reaches of the Saigon River in 1997,^[52] and no similar studies were available to represent the lower portions of the river. Second, the EDI estimation under the assumptions^[36] of daily consumption of metal-contaminated water (3 L for adults and 1 L for children), its continuous duration (18 years for children and 52 years for adults), and average body weight (10 kg for children and 55 kg for adults) may be unrealistic as the majority of people living near the river utilize standard tap water for personal use. Nevertheless, these assumptions may be helpful in warning certain specific communities that use river water of the potential risks. Nevertheless, the method has been validated in many other studies.^[14,15,36,53] Finally, the pollution sources of the TMs were not identified in the present study, which warrants future studies to identify the point and non-point pollution sources in order to minimize the risks.

5. Conclusions

In addition to the spatial variation, the seasonal change played an important role in determining the ecological and human health risks of the metal pollution of the Saigon River surface water. The RI value was higher in the dry season than in the rainy season and exceeded the threshold of 150. Although the HQ value for the individual metals was < 1 , indicating that the human health risk could be presumed to be minimal, the HI value for children was > 1 , suggesting that children's health could be vulnerable to the harmful effects of the current metal status of the river surface water. Since the last measurement in 2013, the concentrations of Cu, Mn, and Pb have increased considerably. The RI and HI values considerably varied spatially and temporally; for example, higher RI and HI values in the dry season were observed in some sites with more anthropogenic activities than in others. Based on the findings, it is necessary to develop a risk-mitigation plan with a strong emphasis on the minimization of water pollution, in particular, Cu water pollution during the dry season. Children's exposure to river water should be carefully monitored to avoid any negative consequences. Overall, the study recommends that an appropriate management plan be developed to prevent the river surface water from becoming more polluted with potentially harmful materials as well as to mitigate the risks to the river ecosystem and public health.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

N.V.N. contributed to data curation, formal analysis, investigation; software, writing—original draft, and writing—review & editing. N.V.T. contributed to funding acquisition, investigation, resources, visualization, writing—original draft, and writing—review and editing.

Data Availability Statement

Data available on request from the authors.

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