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Pollution and Potential Ecological Risk Assessment of Heavy Metals in Water Bodies in the Vicinity of Industrial Zones

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Abstract

This research was undertaken to determine the concentrations of heavy metal ions in the surface water and sediment in water bodies that receive wastewater from the Dinh Tram and Pho Noi A industrial zones. The pollution status of the heavy metal ions and their potential ecological risks were evaluated by using the potential ecological risk index (RI) and risk assessment code (RAC). The results showed that some metal ions, namely Fe^{3+}, Ni^{2+}, and Pb^{2+}, exceeded the allowed standards of QCVN 08:2023/BTNMT. The sediments were polluted by Zn^{2+}, As^{2+}, Cr^{6+}, and Fe^{3+} at concentrations 2.4, 3.7, 1.9, and 2.0 times higher, respectively, than the QCVN 43:2017/BTNMT. The potential ecological risk indices for the heavy metal ions were in order as: (As^{2+}) = 7.94 > (Cd^{2+}) = 3.68 > (Cr^{6+}) = 3.39 > (Pb^{2+}) = 2.73 > (Cu^{2+}) = 2.74 > (Zn^{2+}) = 2.4 (T6 channel) and (As^{2+}) = 11.1 > (Cd^{2+}) = 7.74 > (Cu^{2+}) = 2.64 > (Cr^{6+}) = 2.31 > (Pb^{2+}) = 1.9 > (Zn^{2+}) = 0.87 (Bun River). The risk assessment code (RAC) ranged from 0.17 to 39.42 (T6 channel) and from 0.03 to 38.96 (Bun River). The RAC-based risk assessment results showed that both the T6 channel and Bun River presented a medium risk for Cd^{2+}, a low risk for Mn^{2+}, Zn^{2+}, Cu^{2+}, and Ni^{2+}, and no risk for the remaining metals, Cr^{6+}, Pb^{2+}, As^{2+}, and Fe^{3+}. These results were caused by the differences in environmental quality assessments between using separate parameters versus biological risk assessments.

Keywords

Ecological risk assessment, heavy metal, accumulation, sediment, industrial wastewater

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Introduction

At the end of 2020, Vietnam had 369 industrial zones, of which 90.96% of them were equipped with waste water treatment plants with a total capacity of more than 1.1 million m^3 day^{-1}. However, industrial zones have still had significant impacts on the natural environment and ecosystems surrounding these areas (Ministry of Natural Resources and Environment, 2021). Heavy metals, especially non-essential ones, can have toxic impacts even at low concentrations (Bharti & Sharma, 2022). Published literature has shown the accumulation of heavy metal ions in urban and industrial treated and untreated wastewater and sediments from sites around Vietnam. In the Nhue River, the concentrations of Pb^{2+} and Zn^{2+} in the sediment were, respectively, 1.7 and 3.9 times higher than the allowed standards of QCVN 43:2017/BTNMT, while the concentrations of these ions in the water were only a few mg L^{-1} (Nguyen Thi Hieu, 2013). Similarly, in the Cau River basin, high levels of the heavy metal ions Zn^{2+}, Pb^{2+}, Cu^{2+}, and Cd^{2+} accumulated in sediments at ranges of 176.4-570.7, 137.7-436.4, 116.6-430.1, and 1.97-5.62 mg kg^{-1}, respectively (Duong Thi Tu Anh & Cao Van Hoang, 2015). In the To Lich and Kim Nguu rivers, while the concentrations of As^{2+}, Fe^{3+}, and Pb^{2+} in the water exceeded the allowable standards of QCVN 08-MT:2015/BTNMT column B1, the contents of these ions in sediments were still lower than the allowed standards of QCVN 43: 2017/BTNMT. In the Kim Nguu River, while the concentration of Zn^{2+} in the surface water was lower than QCVN 08-MT:2015/BTNMT, the concentration of this ion in the sediment exceeded QCVN 43:2017/BTNMT (Nguyen Thi Bich Ngoc *et al.*, 2015). Concentrations in the surface water and sediments depend on the type of metal as well as the environmental conditions. Heavy metal ions that have accumulated in ecosystems might enter the food chain and bioaccumulate in algae (Ngo *et al.*, 2009; Ngo Thi Thuy Huong *et al.*, 2016), crustaceans (Ngo Thi Thuy Huong *et al.*, 2016; Nguyen Phuc Cam Tu, 2023), and fish (Pham Kim Dang *et al.*, 2015). Heavy metal ions in sediments can be introduced into the natural environment, which can cause adverse effects on aquatic ecosystems (Mohammed & Markert, 2006), and account for a significant source of toxic compounds for living organisms. The absorption and accumulation of heavy metals in plants affect their metabolic activity and reduce agricultural crop yield (Guala *et al.*, 2010). In this study, both essential (such as Mn^{2+}, Cu^{2+}, Fe^{3+}, and Zn^{2+}) and non-essential (such as Pb^{2+}, As^{2+}, Cd^{2+}, and Cr^{6+}) heavy metal ions were selected to determine their concentrations in surface water and the corresponding sediments.

An ecological risk assessment includes an assessment of the hazards posed by the presence of chemicals released into the environment, and how the environment will be affected by the presence of one or more stressors. The potential ecological risk index (RI) is a methodology developed by Hakanson (1980) to evaluate the ecological risks of heavy metals in sediments. A risk assessment code (RAC) is a method for the risk assessment of heavy metals (Singh *et al.*, 2005). Risk assessment is often based on the chemical characteristics of heavy metals. Recent studies have evaluated heavy metal pollution in sediments in terms of their total content, using total content as a criterion to assess their potential impact on the environment. However, the total content of heavy metals does not provide sufficient information to assess their bioavailability and toxicity. In this study, the assessment results will be beneficial for the management and control of heavy metal pollution in both surface water and sediments in the water bodies receiving wastewater from industrial zones.

Methodology

The study sites were located in Bac Giang and Hung Yen provinces, in Northern Vietnam (**Figure 1**). The T6 channel and Bun River receive wastewater from the Dinh Tram and Pho Noi A industrial zones (IZ), respectively. Both Dinh Tram (2,000 m^3 day^{-1} of wastewater discharged) and Pho Noi A (6,000 m^3 day^{-1} of treated wastewater discharged) mainly include electronic component manufacturing and mechanical factories. Since the T6 channel and Bun River are water channels for agricultural irrigation, it is very important to control the quality of surface water resources.

Research Materials

Water samples

Seven surface water samples were collected at the T6 channel (M1-M4), which receives wastewater from the Dinh Tram industrial zone, and the Bun River (M5-M7), which obtains wastewater from the Pho Noi A industrial zone, in March of 2023. The surface water samples for

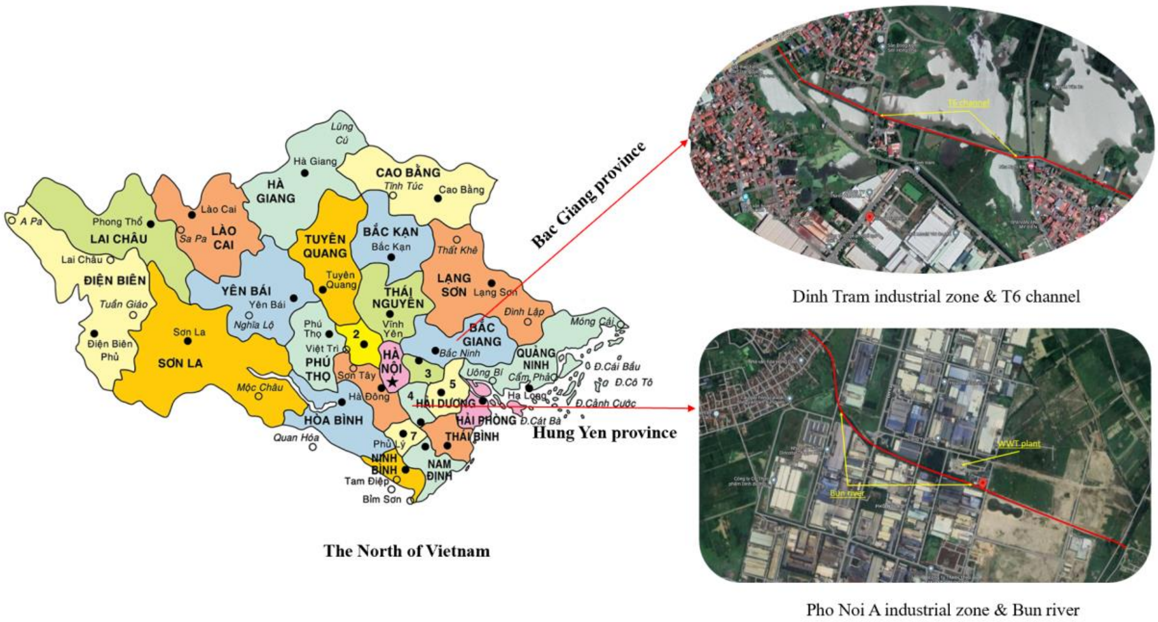

Figure 1. Study sites

Table 1. Locations for sampling surface water

No	Location	Coordinates		Note
M1	Dinh Tram IZ	21°15'47.9"N	106°07'28.5"E	In the sewer
M2	Dinh Tram IZ	21°15'50.8"N	106°07'29.6"E	100m from the sewer
M3	Dinh Tram IZ	21°15'49.8"N	106°07'35.0"E	400m from the sewer
M4	Dinh Tram IZ	21°15'52.2"N	106°07'25.2"E	Irrigation drain to Duc Lien
M5	Pho Noi A IZ	20°57'14.5"N	106°01'55.2"E	In the sewer
M6	Pho Noi A IZ	20°57'06.9"N	106°02'15.6"E	600m from the sewer
M7	Pho Noi A IZ	20°57'02.7"N	106°02'27.2"E	Irrigation drain to Chua village

Figure 2. Sampling sites

the experiment were collected following TCVN 6663-1:2011. Samples were taken from the shore with a stick and water sampler device at a depth of 20cm below the water level and placed in cold storage in a 1 liter, dark-colored container. The detailed information on the surface water samples is described in **Table 1** and **Figure 2**.

Sediment samples

The locations of sediment sampling were the same sites as the surface water sampling. Sediment samples were collected by using an Ekmans bucket 196-F62 with a capacity of 5.3 liters. The sediment samples for the experiment were collected following TCVN 6663-15:2004. The samples were collected at a 0-10cm depth in the sediment-water interface and stored in plastic containers. Large particles and debris were removed via 2mm sieves, air-dried, and then homogenized before analyzing.

Research Methods

Sequential extraction concentration (F1, F2) of heavy metal ions

Heavy metal ion concentrations were fractionated into two parts, F1 and F2, following the methods of Tessier *et al.* (1979). The sequential extraction procedure is shown in **Figure 3**.

Heavy metal concentration analysis

Heavy metals in the surface water were directly analyzed by US EPA Method 3051 (microwave-assisted acid digestion) and US EPA Method 6020A (inductively coupled plasma mass spectrometry). Five milliliters of each surface water sample was mixed with 10ml of aqua-regia solution (HNO_3:HCl=1:3) and then slowly heated to 200^{o}C in a microwave digestion system. Sediment samples were air-dried and then passed through a 2mm sieve. Two grams of each dried sediment sample was mixed with 20ml H_2O_2 to remove any organic matter, then mixed with 10ml of1M CH_3COONH_4 solution, and slowly heated to 200^{o}C in a microwave digestion system. The extracted solution after digestion was examined by inductively coupled plasma mass spectrometry (ICP-MS). All experiments were performed in triplicate.

Ecological risk assessment (RI)

A potential ecological risk index (RI) was used as a diagnostic tool for water pollution assessment purposes. The index was recommended by Hakanson (1980). The value of RI can be calculated by the following formulas and is clarified in **Table 2**:

$$C_f^i = \frac{C_D^i}{C_R^i};\ E_r^i = T_r^i \times C_f^i \text{ and } RI = \sum_{i=1}^{m} E_r^i$$

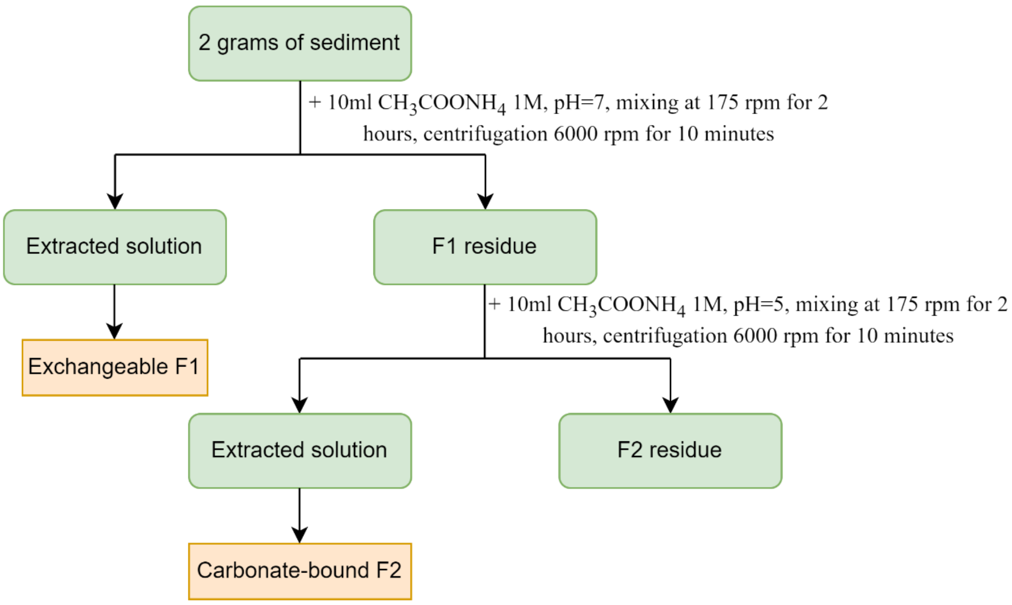

Figure 3. Sequential extraction of heavy metals (Tessier *et al.*, 1979)

Table 2. Indices and grades of potential ecological metal contamination

E_r^i	Grade of ecological risk of a single metal	RI value	Grade of potential ecological risk of environment
$E_r^i < 40$	Low risk	RI < 150	Low risk
$40 \leq E_r^i < 80$	Moderate risk	150 ≤ RI < 300	Moderate risk
$80 \leq E_r^i < 160$	Considerable risk	300 ≤ RI < 600	Considerable risk
$160 \leq E_r^i < 320$	High risk	RI ≥ 600	Very high risk
$E_r^i \geq 320$	Very high risk	-	

Table 3. Classification of RAC (%)

No	Metal ions in the exchangeable (F1) and carbonate-bound (F2) fractions	Risk
1	< 1	No risk
2	1-10	Low risk
3	11-30	Medium risk
4	31-50	High risk
5	> 50	Very high risk

where RI is the sum of potential risks of an individual heavy metal; E_r^i is the potential risk of an individual heavy metal; T_r^i is the toxic-response factor for a given heavy metal (Hakanson, 1980); C_f^i is the contamination coefficient; C_D^i is the present concentration of heavy metals in the sediments; and C_R^i is the pre-industrial record of heavy metal concentration in the sediments.

Risk assessment code (RAC)

Risk assessment code (RAC) is defined as the total fraction of exchangeable (F1) and carbonate-bound (F2) metals. According to the guidelines of the RAC method, for any metal, where the total fractions of exchangeable and carbonate-bound are less than 1%, there is no risk, but when this ratio is greater than 50%, the level of risk is assessed as very high and heavy metals are easily able to be released and enter the food chain. The level of risk to the ecosystem was assessed based on two types of fractions, exchangeable (F1) and carbonate-bound (F2), through the %RAC index (Perin *et al.*, 1985) as shown in **Table 3**.

Results and Discussion

Heavy metal in surface water

The results of the heavy metal ion concentrations in the surface water are summarized in **Table 4**. In general, some heavy metal concentrations, namely Cu^{2+}, Zn^{2+}, As^{2+}, and Cd^{2+}, were still below the permissible standard thresholds, while others, namely Pb^{2+}, Mn^{2+}, Ni^{2+}, Cr^{6+} and Fe^{3+}, were from 1.1 to 4.7 times higher than the allowed standards. Surface water in the T6 channel and Bun River were not polluted by Cu^{2+}, Zn^{2+}, As^{2+}, Mn^{2+}, Cr^{6+}, or Cd^{2+} in comparison with the National Technical Regulations on surface water quality - QCVN 08:2023/BTNMT. However, the concentrations of some ions, namely Fe^{3+} and Ni^{2+}, exceeded the allowed standards. The surface water was polluted by Fe^{3+} and Ni^{2+} at approximately 1.62 and 1.2 times as much as QCVN 08:2023/BTNMT.

Iron (Fe) had 6/7 samples while Ni^{2+} and Pb^{2+} had only 1/7 locations that exceeded the allowed standards. The locations that exceeded the standards were all located in the wastewater sewer of the industrial zones. The remaining locations adjacent to the agricultural area (M3 , M4, and M7) were within the allowed standards. The high concentration of Fe^{3+} might be explained by the application of ferric sulfate ($Fe_2(SO_4)_3.nH_2O$) as an iron-based coagulant in wastewater treatment systems (Rizzo *et al.*, 2008) in both industrial zones.

Heavy metal contents in sediment

The results analyzing the heavy metal ions in the sediments are summarized in **Table 5**. The concentrations of heavy metals in the sediment samples were compared with the

Table 4. Heavy metal concentrations in surface water (mg L^{-1})

No	Parameters	Average concentration (Mean ±SD)		QCVN 08:2023/BTNMT
		T6 channel (n=4)	Bun River (n=3)	
1	Cu^{2+}	0.057 ± 0.052	0.04 ± 0.006	0.1
2	Pb^{2+}	0.026 ± 0.017	0.039 ± 0.025	0.02
3	Zn^{2+}	0.199 ± 0.111	0.215 ± 0.037	0.5
4	As^{2+}	0.0026 ± 0.0007	0.0073 ± 0.0035	0.01
5	Mn^{2+}	0.167 ± 0.108	0.267 ± 0.156	0.1
6	Ni^{2+}	0.117 ± 0.081	0.089 ± 0.011	0.1
7	Cr^{6+}	0.12 ± 0.04	0.078 ± 0.034	0.05
8	Cd^{2+}	0.0042 ± 0.0014	0.0024 ± 0.0017	0.005
9	Fe^{3+}	1.83 ± 0.84	2.43 ± 1.48	0.5

National Technical Regulations on Sediment Quality - QCVN 43:2017/BTNMT on Sediment Quality for Heavy Metals to assess the pollution level as well as the accumulation of heavy metals in water bodies. Compared with other studies in Vietnam on the content of heavy metals in sediment, the results in this study were much higher than those in Day River sediment with reported values of Cu^{2+}: 15.8-82.6; Pb^{2+}: 13.1-72.1; Cd^{2+}: 0.2-2.43; and Cr^{6+}: 16.1-97.3 mg kg^{-1} (Le Thi Trinh *et al.*, 2018). The results in this study are quite similar to the research results of Duong Thi Tu Anh & Cao Van Hoang (2015) who studied the Cau River area, Thai Nguyen province and also reported high concentrations of heavy metals in the sediments with values of Zn^{2+}: 176.40-570.70; Pb^{2+}: 137.66-436.43; Cu^{2+}: 116.55-430.13; and Cd^{2+}: 1.97-5.62 mg kg^{-1}.

Fractionated (F1, F2) concentrations of heavy metals in sediment

The results of the analysis of heavy metal concentrations in the exchangeable (F1) and carbonate–bound (F2) fractions of the seven sediment samples from the T6 channel and Bun River are shown in **Table 6**. It can be seen from the table that the availabilities of metals in the sediment were at low concentrations. Most of the heavy metals had a higher exchangeable form (F1) than a carbonate-bound form (F2). Aquatic organisms are exposed to biological metals that are dissolved in water, associated with suspended particles, or deposited in bottom sediments. These certain metals can be bioaccumulated, biomagnified, or biotransformed to concentration levels high enough to bring about harmful effects (Naimo, 1995).

Ecological risk assessment

In this study, an ecological risk assessment was conducted by using the potential ecological risk index (RI) and risk assessment code (RAC). The results of these two indices are shown in **Table 7**, **Table 8**, and **Figure 4**.

Potential ecological risk index (RI)

The order of ecological risk of each metal in the sediments from the T6 channel was arranged as follows: $\boldsymbol{E_r^i}(As^{2+}) = 7.49 > \boldsymbol{E_r^i}(Cd^{2+}) = 3.68 > \boldsymbol{E_r^i}(Cr^{6+}) = 3.39 > \boldsymbol{E_r^i}(Pb^{2+}) = 2.73 > \boldsymbol{E_r^i}(Cu^{2+}) = 2.74 > \boldsymbol{E_r^i}(Zn^{2+}) = 2.4$. Arsenic was the most ecological risk factor at channel T6. In the Bun River, the ecological risk of each metal in the sediments was arranged in the following order: $\boldsymbol{E_r^i}(As^{2+}) = 11.1 > \boldsymbol{E_r^i}(Cd^{2+}) = 7.74 > \boldsymbol{E_r^i}(Cu^{2+}) = 2.64 > \boldsymbol{E_r^i}(Cr^{6+}) = 2.31 > \boldsymbol{E_r^i}(Pb^{2+}) = 1.9 > \boldsymbol{E_r^i}(Zn^{2+}) = 0.87$. Arsenic was also the most ecological risk factor at the Bun River. The results of the ecological risk assessment by sediments in the T6 channel and Bun River had low levels of risk for the analyzed metal ions. Of which, As^{2+}, Cd^{2+}, Cu^{2+}, Pb^{2+}, and Cr^{6+} had higher degrees of ecological risk contribution than the other remaining elements.

In the T6 channel, the RI results decreased as the distance increased from the discharge point: RI_{M1}=38.87; RI_{M2}=20.98; RI_{M3}=16.55; and RI_{M4}=15.48. The potential ecological risk indices

Table 5. Heavy metal ion contents in sediment (mg Kg^{-1})

No	Parameters	Average concentration (Mean ± SD)		QCVN 43:2017/BTNMT
		T6 channel (n=4)	Bun River (n=3)	
1	Cu^{2+}	107.60 ± 84.26	103.82 ± 29.61	197
2	Pb^{2+}	50.04 ± 20.76	34.74 ± 3.02	91.3
3	Zn^{2+}	755.03 ± 816.32	274.064 ± 59.44	315
4	As^{2+}	40.37 ± 18.76	63.73 ± 43.65	17
5	Mn^{2+}	148.30 ± 84.08	564.05 ± 206.91	-
6	Ni^{2+}	87.90 ± 85	76.33 ± 11.98	-
7	Cr^{6+}	176.84 ± 129.37	103.95 ± 18.73	90
8	Cd^{2+}	0.43 ± 0.17	0.9027 ± 0.86	3.5
9	Fe^{3+}	40,194.5 ± 1,329.1	38,599.9 ± 7,856.16	20,000

(RI) for metals varied from 15.48 to 38.87, showing that this area had a low level of risk (RI < 150) for the heavy metals Cu^{2+}, Pb^{2+}, Zn^{2+}, As^{2+}, Cr^{6+}, and Cd^{2+}. The RI results in this study are similar to those of Le Thi Trinh *et al*. (2018) in the downstream area of the Day River.

Risk assessment code (RAC)

Through the analysis results, it was seen that although the total heavy metal content in the sediments was high for Zn^{2+}, Cu^{2+}, and Mn^{2+}, the two fractions of binding that are easily released in the sediment and then in the water, the F1 and F2 fractions, accounted for only a small percentage of less than 11.2%. The order of heavy metal fractionation/total content ratio in the sediment was arranged as follows: Fe^{3+} (0.03%); As^{2+} (0.47%); Pb^{2+} (0.50%); Cr^{6+} (0.63%); Ni^{2+} (1.35%); Cu^{2+} (1.77%); Zn^{2+} (2.50%); and Cd^{2+} (11.20%) (**Table 8**). It has been suggested that the speciation of a metal is the main information to determine its effects (Allen & Hansen, 1996) as well as its biogeochemical transformation (Billon *et al.*, 2002). The results of this study are quite similar to the study of Duong Thi Tu Anh & Cao Van Hoang (2015) in the Cau River area when the total contents of the F1 and F2 fractions ranged from 10 to 30%.

From **Table 8**, the average value of the RAC index of the metals was in the order of Cd^{2+} > Mn^{2+} > Zn^{2+} > Cu^{2+} > Ni^{2+} > Pb^{2+} > Cr^{6+} > As^{2+} > Fe^{3+}. In the T6 channel, the heavy metals Cd^{2+}, Mn^{2+}, Zn^{2+}, Cu^{2+}, and Ni^{2+} had %RAC in the range of 1- 10%, and their level of risk was low. The remaining metals, namely Pb^{2+}, Cr^{6+}, As^{2+}, and Fe^{3+}, had no risks as their RAC values were less than 1%.

In the Bun River, Cd^{2+} was at a medium-risk level with a %RAC of 12.99%, which was in the range of 11 – 30%, while the RAC indices of Mn^{2+}, Zn^{2+}, Cu^{2+}, and Ni^{2+} were in the range of 1 – 10% with low-risk levels. The other remaining metal ions (As^{2+}, Cr^{6+}, Pb^{2+}, and Fe^{3+}) were all no-risk with %RAC less than 1%. In both the T6 channel and Bun River, there was a medium risk of Cd^{2+}, low risk of Mn^{2+}, Zn^{2+}, Cu^{2+}, and Ni^{2+}, and no risk for the remaining metals of Cr^{6+}, Pb^{2+}, As^{2+}, and Fe^{3+}. The study of Duong Thi Tu Anh & Cao Van Hoang (2015) on the heavy metal content in Cau River sediments showed the RAC values were higher than those in this study, ranging from 8.11 to 14.47%, but no area was rated as a high-risk level.

An assessment of potential ecological risks of heavy metals in a body of water shows the levels of potential risks affecting the aquatic ecosystem when the sediment is contaminated with heavy metals. In this study, 5/9 heavy metal ions exceeded the permissible limits. The results of the RI assessment showed that the T6 channel and Bun River areas were assessed as having a low risk when the RI values ranged from 15.48 to 38.87 (<150). None of the metal ions were rated at medium or high risk. However, if evaluated based on the RAC index, the T6 channel and Bun River areas were assessed as

Table 6. Fractionated concentrations of heavy metal ions in sediment (mg Kg^{-1})

	Sample	Average Concentration (Mean ± SD)						
		M1	M2	M3	M4	M5	M6	M7
Exchangeable (F1)	Cu^{2+}	1.850 ± 0.130	1.260 ± 0.150	1.030 ± 0.090	0.860 ± 0.080	1.590 ± 0.110	1.040 ± 0.030	1.680 ± 0.300
	Pb^{2+}	0.340 ± 0.08	0.280 ± 0.080	0.030 ± 0.010	0.046 ± 0.010	0.070 ± 0.020	0.010 ± 0.000	0.010 ± 0.000
	Zn^{2+}	8.290 ± 0.560	25.100 ± 2.430	5.640 ± 0.870	8.910 ± 0.980	7.460 ± 0.660	3.300 ± 0.640	4.880 ± 0.460
	As^{2+}	0.010 ± 0.005	0.020 ± 0.002	0.020 ± 0.010	0.030 ± 0.003	0.090 ± 0.004	0.060 ± 0.004	0.050 ± 0.003
	Mn^{2+}	2.800 ± 0.440	8.870 ± 0.350	3.130 ± 0.400	8.820 ± 0.570	27.700 ± 2.360	14.000 ± 0.860	26.200 ± 2.150
	Ni^{2+}	0.450 ± 0.050	0.550 ± 0.070	0.340 ± 0.080	0.300 ± 0.050	0.830 ± 0.070	0.740 ± 0.050	1.030 ± 0.050
	Cr^{6+}	0.200 ± 0.030	0.400 ± 0.060	0.450 ± 0.050	0.420 ± 0.040	0.440 ± 0.040	0.390 ± 0.020	0.390 ± 0.040
	Cd^{2+}	0.010 ± 0.005	0.040 ± 0.006	0.040 ± 0.007	0.030 ± 0.005	0.050 ± 0.004	0.030 ± 0.003	0.080 ± 0.007
	Fe^{3+}	1.690 ± 0.800	0.670 ± 0.050	4.380 ± 0.260	1.880 ± 0.120	0.590 ± 0.070	5.760 ± 0.590	0.870 ± 0.070
Carbonate-bound (F2)	Cu^{2+}	1.084 ± 0.120	0.283 ± 0.050	0.145 ± 0.030	0.084 ± 0.020	0.247 ± 0.040	0.267 ± 0.020	0.616 ± 0.070
	Pb^{2+}	0.170 ± 0.030	0.304 ± 0.040	0.138 ± 0.020	0.130 ± 0.020	0.091 ± 0.020	0.089 ± 0.020	0.070 ± 0.020
	Zn^{2+}	2.850 ± 0.140	1.152 ± 0.120	0.627 ± 0.110	0.070 ± 0.010	0.101 ± 0.020	0.168 ± 0.030	0.179 ± 0.020
	As^{2+}	0.016 ± 0.002	0.021 ± 0.002	0.014 ± 0.002	0.014 ± 0.001	0.067 ± 0.003	0.056 ± 0.003	0.047 ± 0.002
	Mn^{2+}	0.283 ± 0.040	0.125 ± 0.020	0.129 ± 0.030	0.046 ± 0.030	0.047 ± 0.020	0.471 ± 0.030	0.209 ± 0.030
	Ni^{2+}	0.887 ± 0.005	0.467 ± 0.002	0.101 ± 0.002	0.090 ± 0.003	0.301 ± 0.058	0.341 ± 0.003	0.404 ± 0.003
	Cr^{6+}	0.969 ± 0.010	0.595 ± 0.060	0.243 ± 0.040	0.263 ± 0.020	0.247 ± 0.020	0.252 ± 0.030	0.247 ± 0.030
	Cd^{2+}	0.008 ± 0.001	0.006 ± 0.001	0.004 ± 0.001	0.008 ± 0.001	0.010 ± 0.002	0.008 ± 0.001	0.009 ± 0.001
	Fe^{3+}	7.731 ± 0.013	28.498 ± 1.506	11.524 ± 1.590	6.267 ± 0.963	0.703 ± 0.025	1.005 ± 0.040	1.676 ± 0.082

Table 7. Potential ecological risk index (RI)

	Sample	E_r^i						RI
		Cu^{2+}	Pb^{2+}	Zn^{2+}	As^{2+}	Cr^{6+}	Cd^{2+}	
Channel T6	M1	5.76	4.01	6.16	9.37	8.09	5.48	38.87
	M2	2.71	3.38	2.08	6.80	3.60	2.42	20.98
	M3	1.23	1.93	0.69	7.96	2.23	2.51	16.55
	M4	1.22	1.64	0.66	5.84	1.80	4.32	15.48
	Average	2.73	2.74	2.4	7.49	3.39	3.68	
Bun River	M5	2.50	1.71	1.01	10.01	2.53	4.14	21.90
	M6	1.96	1.98	0.66	9.67	1.83	16.23	32.31
	M7	3.44	2.02	0.95	13.61	2.57	2.85	25.44
	Average	2.64	1.9	0.87	11.1	2.31	7.74	

Table 8. Ratio of fractionation/total content of heavy metal ions (%)

	Sample	Cu^{2+}	Pb^{2+}	Zn^{2+}	Cd^{2+}	As^{2+}	Mn^{2+}	Ni^{2+}	Fe^{3+}	Cr^{6+}
	M1	1.29	0.69	0.57	2.78	0.18	1.17	0.64	0.02	0.32
T6 channel	M2	1.45	0.94	4.02	14.99	0.40	5.74	1.25	0.09	0.62
	M3	2.42	0.47	2.87	14.22	0.26	3.94	1.30	0.03	0.69
	M4	1.95	0.45	4.31	7.43	0.44	9.90	1.49	0.03	0.84
Sub average		*1.78*	*0.64*	*2.94*	*9.86*	*0.32*	*5.18*	*1.17*	*0.04*	*0.62*
Bun river	M5	1.86	0.50	2.38	11.50	0.92	3.22	1.51	0.00	0.61
	M6	1.69	0.26	1.68	1.75	0.70	3.96	1.65	0.02	0.78
	M7	1.69	0.20	1.70	24.71	0.42	5.65	1.61	0.01	0.55
Sub average		*1.75*	*0.32*	*1.92*	*12.99*	*0.68*	*4.28*	*1.59*	*0.01*	*0.65*
Average		1.77	0.50	2.50	11.20	0.47	4.80	1.35	0.03	0.63

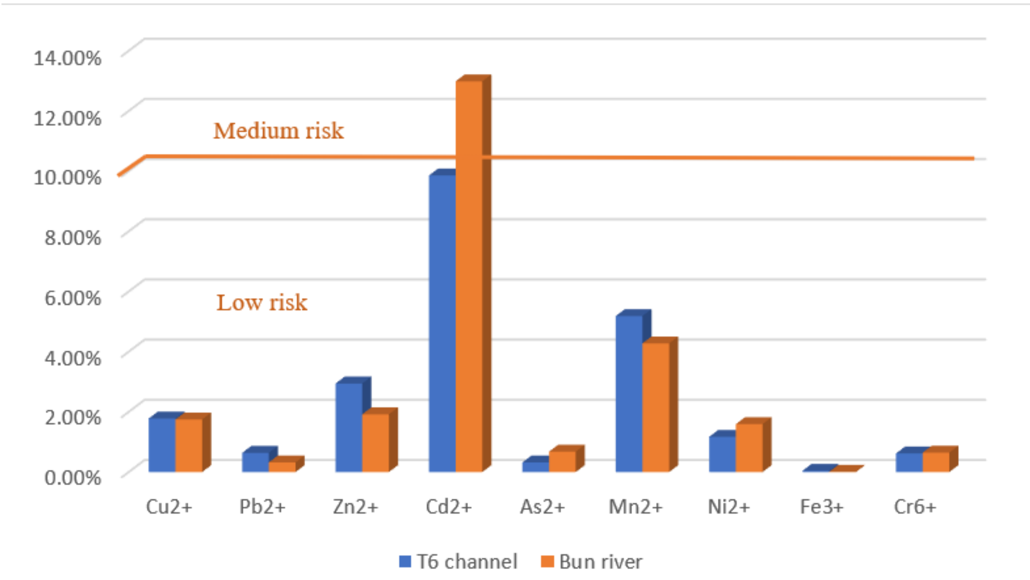

Figure 4. Risk assessment code (RAC) in the T6 channel and Bun River

having a high risk for Cd^{2+}, medium risk for Mn^{2+} and Pb^{2+}, and low risk for the other elements. The RI is based only on the total metal concentration value, while the RAC assesses the risk based on the concentrations of exchangeable and carbonate-bound metals. Ecological risk assessment based on bioavailability content makes more sense than using an assessment based on the total concentration.

The metal accumulation characteristics of sediments as well as potential risks that could have negative impacts on water bodies and on using the water for agricultural purposes should be further analyzed in the future.

Conclusions

The initial results of this study showed that although the water bodies receive wastewater from the Dinh Tram and Pho Noi A industrial zones, the surface water quality in these two water bodies, the T6 channel and Bun River, were not polluted by the heavy metals Cu^{2+}, Zn^{2+}, As^{2+}, Mn^{2+}, Cr^{6+}, and Cd^{2+}. There were, however, signs of slight pollution by other metals, namely Fe^{3+}, Ni^{2+}, and Pb^{2+}. Although the quality of the surface water environment showed signs of slight pollution by Fe^{3+}, Ni^{2+}, and Pb^{2+}, the sediments were polluted by other heavy metals, namely Zn^{2+}, As^{2+}, Cr^{6+}, and Fe^{3+}, at concentrations 2.4, 3.7, 1.9, and 2.0 times higher, respectively, than the allowed standards according to QCVN 43:2017/BTNMT.

In terms of RI assessment, which is applied for evaluating the risk of heavy metals in surface water, the results showed that although both water bodies were valued as slightly polluted for Fe^{3+}, Ni^{2+}, and Pb^{2+} (according to QCVN 43:2017/BTNMT), the results based on RI (assessment for each parameter) showed that the risk of pollution was at a low risk (combined assessment of heavy metal parameters) as the RI values varied from 15.48 to 38.87. Heavy metal contents in terms of exchangeable (F1) and carbonate-bound (F2) were used to determine the risk of the sediment according to the RAC method. The RAC-based risk assessment results showed that both the T6 channel and Bun River presented a medium risk for Cd^{2+}, a low risk for Mn^{2+}, Zn^{2+}, Cu^{2+}, and Ni^{2+}, and no risk for other remaining metals of Cr^{6+}, Pb^{2+}, As^{2+}, and Fe^{3+}. In this study, the results of surface water quality assessment based on the potential ecological risk index (RI) and RAC risk assessment had a similar relationship with each other when showing the levels of risk for metals such as Cd^{2+}, Mn^{2+}, and Zn^{2+}. However, for the parameters of As^{2+}, Cr^{6+}, Pb^{2+}, or Cu^{2+}, the RI values were high but the values of RAC were low. These results are very meaningful because of the affection of bioavailability and transformation ability of heavy metals in sediment.

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