Assessment of Heavy Metal Distribution and Development of a Pollution Map for the Downstream Thi Vai River

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***Abstract*—The main contributors to the contamination of rivers with heavy metals include industrial manufacturing, domestic practices, and aquaculture. Based on contemporary research, it has been identified that three primary mechanisms of surface flow facilitate the transportation of pollutants, specifically heavy metals. These mechanisms include dissolved flow, Suspended Particulate Matter (SPM), and bottom flow, which is associated with sediment movement. The primary objective of this study was to assess the spatial distribution and levels of heavy metals in the downstream region of the Thi Vai River. This investigation encompassed the examination of heavy metal concentrations in the dissolved, suspended, and sedimentary fractions. LogKd distribution coefficients and the Geographic Information System (GIS) were used in this study to show how heavy metals were spread out in space along the three sections of the Thi Vai River that flow downstream, which included a total of 19 monitoring sites. The average concentrations of Fe, Mn, Zn, Cu, Ni, Pb, and Cd were 0.193, 0.06, 0.092, 0.056, 0.0095, 0.0028 mg/L respectively in the dissolved phase; 405.7, 269.6, 225.1, 72.2, 61.1, 35.2, 4.7 mg/kg respectively in the suspended phase and 9.8.9, 266.3, 152.7, 79.3, 44.6, 42.2, 3.3 mg/kg respectively in the sediment phase which achieved the national standard averages, except for Cd exceed. It is crucial to acknowledge that heavy metals tend to concentrate predominantly in the suspended phase, resulting in the presence of varied distribution coefficients. Research has shown that anthropogenic activities located along the river are mainly responsible for the presence of heavy metals. The effects of natural processes such as river hydrodynamics on the dispersion and transport of these pollutants remain unknown.**

***Keywords*—heavy metals, Distribution coefficient, GIS, Thi Vai river**

I. Introduction

Surface water is a vital resource that is used for a variety of purposes in daily life, agricultural production, and industry of each country. Natural and human activities can have a combined or individual impact on the quality of surface water [1]. With the current socio-economic development conditions, environmental deterioration has occurred, exacerbating the problem of surface water pollution in river systems. Pollutants to river water sources can come from upstream, including waste dumps, artificial sources, or material exchange between surface water and polluted sediments [2, 3]. Determining quality parameters at the spatial scale is crucial for river basin pollution assessment and current water resource management [4].

Water serves as a medium for physical, chemical, and biological processes such as dissolution, precipitation, absorption, and desorption of particulate matter, as well as complexation with both organic and inorganic agents, which aids in the transportation of contaminants. It also includes aquatic organism absorption as well as suspended materials precipitation or sedimentation. The concentration of heavy metals and other contaminants in the water during transportation may alter significantly as a result of these actions. According to studies conducted by the US Environmental Protection Agency [5], the sorption process of suspended particles can alter the concentration of metals in surface waters. In addition, other studies have shown that a significant proportion (over 90%) of pollutants are transported in suspension, mostly as a result of their direct interaction with the water surface, which contributes to sediment formation.

Three main mechanisms are involved in the transport of contaminants through surface flows: dissolution, suspension (SPM), and sedimentation [6–8], examine how and where pollutants are found in watersheds in all three sections, focusing on suspended particles. SPM is mainly composed of colloidal particles, which may carry contaminants across long distances. The suspended phase within the river cross-section is critical for pollution transfer.

The analysis of pollution in river basins focuses on the complexities associated with the dispersion and transport of pollutants, in which the distribution characteristics must be accurately determined and analyzed. The distribution coefficient K_d (or partition coefficient K_p) shows the movement and dispersion of pollutants between the dissolved state in the liquid phase and the solid phase; the index is often referred to as $\log K_d$ [9]. Studies reveal that heavy metals can bind and adsorb more in various phases due to their high distribution coefficients (K_d and $\log K_d$) [10]. Many studies have shown that the ratio of heavy metals in suspended components to dissolved components has a logKd value that often exceeds 3. This shows that heavy metals tend to form bonds and accumulate mainly with suspended particulate matter (SPM). Several studies in China and Thailand [9–11] have shown a strong correlation between heavy metals and SPM with $\log K_d$ values higher than 3, and particle size and ionic radius are two contributing factors. The K_d values of sediment-water interactions were consistently lower than those of SPM and water for ten heavy metals, including arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), antimony (Sb), and zinc (Zn). Therefore, SPM is more effective in removing heavy metals and inorganic pollutants due to its smaller particles, larger contact surface area, and higher organic matter content [10, 12]. This shows that Suspended

Particulate Matter (SPM) is the primary route for transferring contaminants and heavy metals.

In Vietnam, studies on the transport of heavy metal-related pollutants in dissolved components, SPM, and sediments are still quite limited compared to studies in the world. This shows that most water quality assessments often prioritize the examination of the dissolved phase and debris while not considering the suspended phase.

The socioeconomic growth of the Southeast coastal area in general and the province of Ba Ria-Vung Tau in particular is significantly influenced by the downstream Thi Vai River. Because of its navigable character, this region has a large number of ports, wharves, industrial complexes, and other economic institutions. In addition to its function of developing the marine economy, the Thi Vai River basin is impacted by a variety of wastewater discharge activities, including industrial, aquaculture, residential, and urban wastes. According to data from the Center for Natural Resources and Environment Monitoring of Ba Ria-Vung Tau Province in the period of 2017–2021, the water quality in this area generally still meets the requirements for domestic water supply purposes, but appropriate treatment technology must be applied or for purposes such as irrigation, meeting the technical standards for surface water stated in the National technical regulation on Surface water quality [13] – column A2. However, some parameters still exceed the permissible limits, such as total suspended solids (TSS), nutrient pollutants such as $N\text{-}NH_4$ and $N\text{-}NO_2$, as well as particular heavy metal concentrations. Under current conditions in the area, the expanding industries driven by economic growth have created favorable conditions for the increase of heavy metals in water, suspended particles, and sediments. With existing studies on water quality in the Thi Vai River basin, there is still a lack of detailed analysis of the spatial distribution of pollutants. Therefore, for a thorough assessment, it is required to analyze the dispersion patterns of heavy metals in water, encompassing all three main components. This manuscript's originality is rooted in its thorough evaluation of heavy metal pollution in the downstream section of the Thi Vai River by a multi-phase analytical methodology. It specifically incorporates the dissolved phase, Suspended Particle Matter (SPM), and sediment phases to assess the distribution of heavy metals. The research is distinctive in utilizing Geographic Information System (GIS) technology to create comprehensive spatial distribution maps of heavy metals, emphasizing pollution hotspots. Additionally, it calculates distribution coefficients (logKd) to quantify heavy metal partitioning, offering insights into their transport and accumulation patterns, especially in an area with active industrial operations. This comprehensive approach provides a more complete perspective on environmental pollution in a developing nation such as Vietnam, which has been insufficiently examined in comparable research.

II. Materials and Methods

A. Research Materials

The objective of this study is to collate and integrate data and documents about the research domain, primarily focusing on the downstream segment of the Thi Vai River. Nineteen sampling monitoring sites, which are deemed representative of the study area, have been chosen. These sites were carefully selected based on positions affected by wastewater sources in the river basin that were surveyed in the field as well as current monitoring positions listed in reports from the Ba Ria-Vung Tau province's Center for Natural Resources and Environment Monitoring (from 2017 to 2021).

The sampling procedure will involve the collection of both water and sediment samples, with a specific emphasis on heavy metal parameters including iron (Fe), zinc (Zn), cadmium (Cd), lead (Pb), copper (Cu), manganese (Mn), and nickel (Ni). The collection procedure conforms to the technical standards of Vietnam, specifically Technical Standards 6663-6:2018 [14]. At each monitoring site, samples representing three components will be collected: dissolved – surface water samples; suspended – SPM, and bottom flow – sediment.

Each water sample will be a combination of 9 locations along the cross-sections of the river, there will be 01 point between the river and 02 points each 2.5m from the bank. Corresponding to each point will be 03 positions corresponding to the depths of 10cm, 20cm, and 30cm according to the vertical cross-section. Sediment samples are samples of riverbed mud 2.5m from the shore at locations in river basins. Sampling frequency is carried out in August (rainy season) and February of the following year (dry season). Fig. 1 depicts a graphical representation of the monitoring sites.

B. Methods for Calculating the Distribution Coefficient

Heavy metals in water are commonly found in two separate phases: the soluble phase and the solid phase, which may consist of suspended particle matter (SPM) or sediment. The distribution coefficient Kd is frequently utilized to quantitatively assess the partitioning between different phases.

As a quantitative way to look at how contaminants move and mix with the soluble, suspended, and sediment parts of river systems, the distribution coefficient Kd is used. This particular parameter is very important because it makes it easier to tell the difference between how heavy metals are distributed, absorbed, and dissolved in liquids and solids.

After analyzing the chemical composition of representative samples for the three components, the distribution factor (K_d) is computed for each pollutant. This calculation serves to clarify the complex mechanisms of distribution and transformation that take place inside the surface flow of the river.

The K_d distribution coefficient of pollutants in the river system is determined according to [15]:

$$K_d = \frac{C_s}{C_d} \quad (1)$$

where:

C_s: Solid phase pollutant content (SPM and sediment) (mg/kg)

C_d: Pollutant content in the dissolved phase (water) (mg/l).

The distribution coefficient is usually expressed as $\log K_d$ (logartite base 10 of K_d) and the higher the $\log K_d$ indicates the greater the adsorption capacity of pollutants in phases and vice versa. In this topic, the distribution coefficient of heavy metals will be expressed in $\log K_d$.

$$\log(K_d) = \log(\frac{C_s}{C_d}) \quad (2)$$

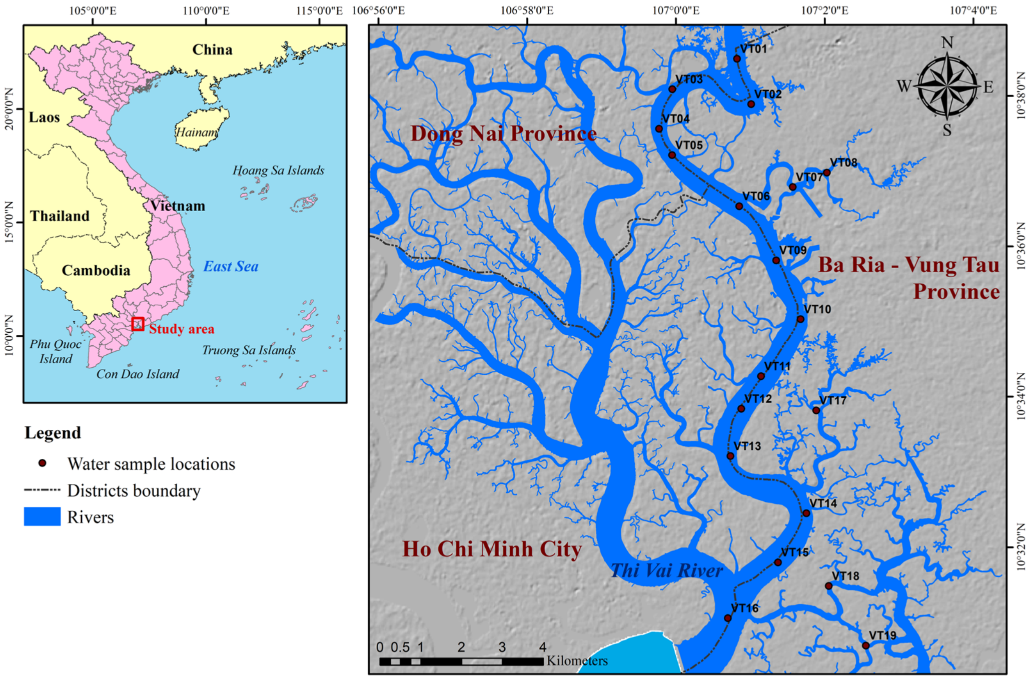

Fig. 1. Location of sampling points.

C. Building Heavy Metal Pollution Partition Maps

The creation of spatial distribution maps for pollution parameters was facilitated through the utilization of ArcGIS software. The Inverse Distance Weighted (IDW) interpolation approach was employed for this purpose. The Inverse Distance Weighting (IDW) approach is a commonly employed and uncomplicated methodology for achieving this objective. By calculating the weighted distance values from known points for each pixel, the IDW technique determines the points to interpolate.

III. Results and Discussion

A. Heavy Metal Content in the Lower Thi Vai River

Some locations downstream of the Thi Vai River do have dissolved-phase concentrations of heavy metals; however, these are extremely low and well within the limitations established by VN technical regulation [13]. Notably, it is worth mentioning that the concentration of iron (Fe) in water samples in the dissolved phase is relatively elevated when compared to other metals. The recorded values range from 0.058 to 0.99 mg/l. On the other hand, it is noteworthy that the concentrations of Cd and Pb exhibit relatively lower values, with a range of 0.0012 to 0.0046 mg/l and 0.0009 to 0.028 mg/l, respectively.

In summary, the quantities of heavy metals in the dissolved phase exhibit an average distribution, with the highest concentrations listed in descending order. The concentration of Fe (0.193 mg/l) is greater than that of Zn (0.092 mg/l), which in turn is greater than Mn (0.06 mg/l), Ni (0.056 mg/l), Cu (0.045 mg/l), Pb (0.0095 mg/l), and Cd (0.0028 mg/l). It is important to highlight that the concentration of heavy metals in the dissolved phase demonstrates negligible variability among the different sampling locations.

The presence of heavy metals is seen in the suspended content of water samples collected from the lower Thi Vai River. The ordering of heavy metal content within the suspended components is as follows: The concentration of iron (Fe) at 405.7 mg/kg is greater than that of manganese (Mn) at 269.6 mg/kg, which in turn is greater than the concentration of zinc (Zn) at 255.1 mg/kg. The concentration of Cu (72.2 mg/kg) is greater than that of Ni (61.1 mg/kg), which is greater than the concentration of Pb (35.2 mg/kg), and finally, the concentration of Cd (4.7 mg/kg) is the lowest. The Zn, Cu, and Ni concentrations in the study area exhibit a comparable pattern to global research; however, the Cd concentration is comparatively elevated and the Pb and Mn concentrations are somewhat diminished in comparison to other regions [9]. In comparison to other metals, the Fe content in the soluble phase exhibits very high concentrations, ranging from 211 to 589 mg/kg. Conversely, Cd and Pb demonstrate the lowest concentrations among the metals, with levels ranging from 2.2 to 8.3 mg/kg and 10 to 64 mg/kg, respectively. The existing regulations do not establish specific limitations for heavy metals in suspended compositions. However, it is generally observed that the concentrations of heavy metals in suspended compositions tend to be higher than those found in sediment. The sample period occurs throughout the dry season, and the water in this region is minimally diluted due to the tidal regime, which causes currents to shift four times per day, and the complicated morphology of the river. Because of this, there are a lot of heavy metals in the suspended matter, and the way the water flows in the Thi Vai River basin may cause or affect the particles in the water to settle to the bottom of the river.

The findings pertaining to the heavy metal concentration in sediment exhibit a resemblance to those obtained from the analysis of the heavy metal concentration in the suspended components. This observation indicates that the accumulation of these elements has occurred at the designated sampling locations. Iron (Fe) consistently exhibits the highest concentration, ranging from 622 to 1,350 mg/kg, whereas cadmium (Cd) consistently exhibits lower values, ranging from 0.9 to 8.6 mg/kg.

The analytical findings indicate that the sediment samples collected from several sites in the lower Thi Vai River exhibit heavy metal concentrations in the following order: The concentration of Fe (908.9 mg/kg) is greater than that of Mn (266.3 mg/kg), which is greater than that of Zn (152.7 mg/kg), Cu (79.3 mg/kg), Ni (44.6 mg/kg), Pb (42.2 mg/kg), and Cd (3.3 mg/kg). It says in QCVN 43:2012/BTNMT that sediment quality in saltwater and brackish water ecosystems must meet certain standards. Heavy metal concentrations in sediment samples from important sampling sites usually fall within those standards. However, it is worth noting that certain locations surpass the permissible standards, specifically the content of Cd.

Notably, the concentration of heavy metals in the sediments of the studied area appears to be relatively lower compared to the results reported in numerous other studies conducted on a global scale. The observed discrepancy can be attributed to the region's prevailing composition of recently deposited sediment [16].

In the wider framework of the lower Thi Vai River region, it is apparent that heavy metals such as iron (Fe) and manganese (Mn) demonstrate elevated levels in comparison to other metallic elements. The observed occurrence can be attributed to the sediment composition present in the river basin, which is characterized by significant quantities of iron oxide and manganese. Additionally, it is important to highlight that the downstream area functions as a point of disposal for specific steel manufacturers located in Phu My town. In contrast, cadmium (Cd) and lead (Pb) exhibit lower concentrations in all three stages, namely dissolved, suspended, and sediment.

B. Distribution of Heavy Metals Lower Thi Vai River

It ranges from 2.71 to 3.87 for Fe, Zn, Cd, Pb, Cu, Mn, and Ni in the SPM/solubility composition to 3.04 to 3.8 for Cd, 2.88 to 3.58 for Cu, 2.8 to 4.54 for Mn, 3.05 to 3.67 for Mn, 3.37 to 3.95 for Ni, and 2.88 to 3.58 for Mn.

We can see that the $\log K_d$ values for lead (Pb), iron (Fe), and manganese (Mn) are much higher in most of the places where they were studied for the heavy metals that are dissolved and suspended in the lower Thi Vai River region. Despite this, the distribution coefficients of dissolved metals and suspended particulate matter (SPM) don't always follow the same pattern or order in different sampling locations. The differences are due to several things, such as changes in the flow regime, changes in the spatial dynamics of tides, and the specific sampling schedule that considers the effects of discharge water flow at the chosen sampling sites.

Moreover, the findings suggest that there is a decrease in the $\log K_d$ distribution factor of suspended particulate matter (SPM) and dissolved metals as the distance from the discharge source increases. It is worth mentioning that areas in closer proximity to the wastewater discharge point of VeDan Company (VT01) demonstrate elevated measurements in comparison to places positioned 1 kilometer downstream from the discharge point of VeDan Company (VT02).

Compared to other sampling sites, VT08—China Steel & Nippon Steel Vietnam Joint Stock Company (CSVC), VT10—Phu My Port, VT11—Thi Vai General Port, VT13—POSCO Port, VT15—Cai Mep Port, and Vina Logistics have a higher SPM/dissolution distribution coefficient for metals. These sites are close to waste sources or inland ports.

Compared to other studies [9–11, 17–23], the $\log K_d$ coefficients for heavy metals in the study area tend to be lower. The observed discrepancy can be attributed to the relatively lower concentration of heavy metals in the suspended components present in the Thi Vai River in comparison to other geographical areas. Furthermore, the input of heavy metals originating from human activities, including industrial operations and maritime transportation, within this region is quite minimal.

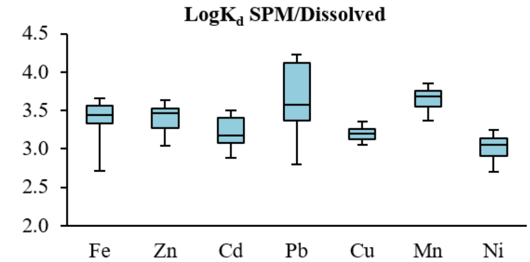

Fig. 2. Distribution chart of the average distribution coefficient of pollutants of SPM and dissolved component lower Thi Vai River.

It is worth mentioning that the logKd values for the samples of SPM (suspended particulate matter) in the lower Thi Vai River constantly surpass a value of 3, as depicted in "Fig. 2". The existing literature [9–11] has demonstrated that when the $\log K_d$ value exceeds 3, there is a higher probability of pollutants binding to suspended particulate matter (SPM). The observed logKd values at the sampling sites exhibit a dominating order as follows: Based on the provided data, the order of the elements in terms of their respective oxidation states is as follows: Pb (3.71) > Mn (3.65) > Fe (3.42) = Zn (3.42) > Cu (3.22) = Cd (3.22) > Ni (3.03).

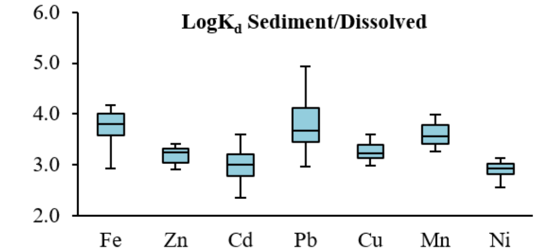

Fig. 3. Distribution chart of the average distribution coefficient of pollutants of the sedimentary and dissolved components of the lower Thi Vai River.

The $\log K_d$ distribution coefficient for sediment/dissolved heavy metals is always greater than a factor of >3 at several sites in the lower Thi Vai River basin, just like it is for SPM/dissolved chemicals in "Fig. 3". Among these coefficients, the logarithm of the dissociation constant ($\log K_d$) for iron (Fe) demonstrates the most elevated values, with lead (Pb) and manganese (Mn) following suit. The occurrence of this phenomenon can be attributed to the significant abundance of iron oxide and manganese in the sediments of the lower Thi Vai River. Iron (Fe) and manganese (Mn) are widely occurring elements in the Earth's crust.

Fe, Zn, Cd, Pb, Cu, Mn, and Ni all had concentration ranges of 2.93 to 4.18, 2.91 to 3.42, 2.35 to 3.6, 2.97 to 4.94, 2.99 to 3.59, 3.26 to 3.99, and 2.56 to 3.14, according to the atomic absorption spectrometry results. The distribution coefficients of heavy metals in the sediment/solubility component exhibit a variety of values. The mean logKd values across the sampling sites are presented below: Based on the provided data, the order of the elements in terms of their respective atomic radii is as follows: The largest atomic radius is that of iron (Fe), which measures 3.78 angstroms, and then that of lead (Pb), which measures 3.77 angstroms. Manganese (Mn) comes next with a value of 3.6 angstroms, followed by copper (Cu) with a value of 3.26 angstroms. Zinc (Zn) has a slightly smaller atomic radius of 3.21 angstroms, followed by cadmium (Cd) with a value of 3 angstroms. Lastly, nickel (Ni) has the smallest atomic radius among the elements listed, with a value of 2.89 angstroms.

It is worth mentioning that the logK_d coefficients observed for the heavy metals investigated in this component tend to have lower values in comparison to the bulk of logKd values documented in previously published studies. The observed disparity can be attributed principally to the fact that the sediment in the lower Thi Vai River region exhibits comparatively lower levels of heavy metal content. Furthermore, the silt in this particular location consists predominantly of recently formed deposits. Moreover, the input of heavy metals originating from human activities, such as industrial operations and shipping, is quite limited within this region.

Researchers from around the world have found that the lower Thi Vai River has a slightly lower distribution coefficient of heavy metals than other places around the world [24–26]. The difference seen is because of the small number of metals that come from different places in the area. This is mostly because of the way inland ports (like Phu My Port, Baria Serece Port, Phuoc Hoa-Dong Bat Port, and Cai Mep Port) work and the wastewater that comes from steel factories (like Pomina, Vina Kyoei, Southern Steel, Posco Yamato Vina, etc.). Furthermore, the region undergoes frequent dredging operations, leading to the predominant transportation of fresh material from upstream to downstream. This silt is shown to have lower levels of metal pollutants in comparison to other regions.

According to the logKd values, the amounts of heavy metals in SPM are usually much higher than the amounts of heavy metals in sediment. This suggests that most of the heavy metals are in the suspended phase. This phenomenon occurs because of the smaller size of SPM particles, resulting in an increased contact surface area and a higher organic matter concentration. This phenomenon facilitates the adhesion of a greater quantity of heavy metals onto these surfaces, hence enhancing their capacity to bind more inorganic contaminants. Fluid dynamics can transport particulate matter, which can then cling to suspended materials and build up over time to form sediment. The strong attraction of heavy metals to both suspended particles and sediments can change depending on the environment. These heavy metals can separate from the suspended particles and sediments and return to the top layer [27].

The silt in the lower Thi Vai River basin is often disturbed as a result of continuous dredging activities, which are necessary due to the presence of multiple inland ports in the area. During the process of dredging, it is possible for certain contaminants to be discharged from the sediment and then transported together with the suspended components. As a result, Suspended Particulate Matter (SPM) assumes a significant function as the principal medium for the transportation of contaminants, specifically heavy metals. The logK_d-Fe value for sediment/dissolved is greater than the logK_d-Fe value for SPM/dissolved. Moreover, the consistently high logK_d-Fe values observed across many locations indicate the stability of iron within the sediment. The significant iron content found in the sediment of this watershed can be linked to the abundance of iron in the Earth's crust.

The heavy metals exhibiting the greatest logKd values in both the suspended particulate matter (SPM)/soluble and sediment/soluble fractions are iron (Fe) and manganese (Mn). This observation potentially indicates that river sediments serve as the predominant reservoir for heavy metal accumulation within the investigated region. In contrast, it can be observed that both Ni and Cd exhibit the most minimal logK_d values comprehensively (Fig. 4).

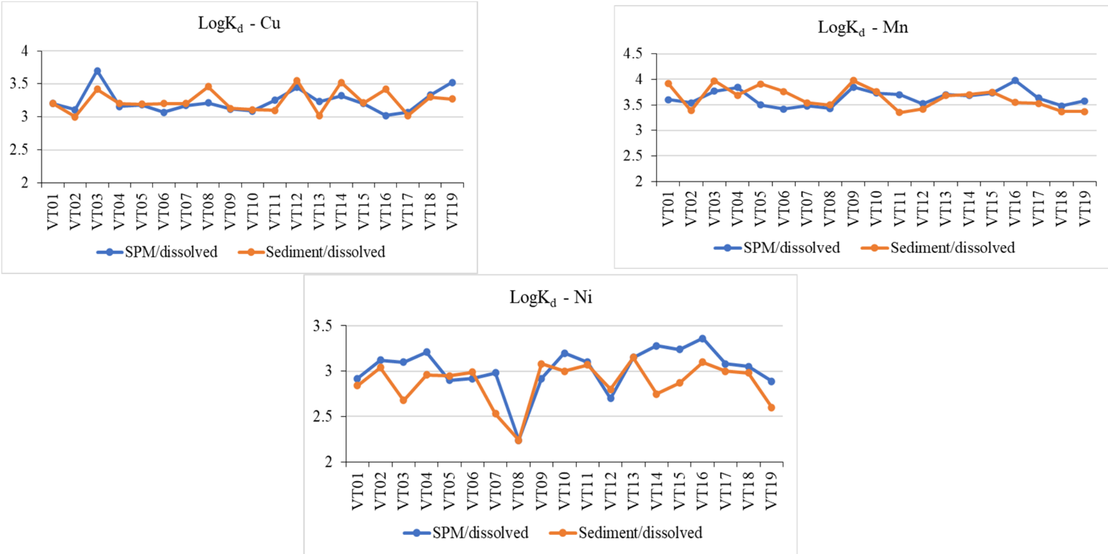

Fig. 4. LogK$_d$ of heavy metals in 2 components at locations downstream of Thi Vai River.

C. Map of Heavy Metal Distribution in the Lower Thi Vai River

By employing the Geographic Information System (GIS) mapping tool, we have successfully determined the geographical dispersion of seven different heavy metals over a total of 19 sampling sites within the Thi Vai River system. By using information gathered from GPS devices, the Gauss coordinate system has georeferenced the aforementioned locations.

The examination of the distribution maps (refer to Figs. A1 through A7, see in appendix) reveals that discharge sources located along the runoff path exert a substantial influence on heavy metal concentrations. The impact of this influence is evident in the elevated levels of various metals, predominantly derived from human activities (mainly originating from inland ports and industry), at these particular sites as compared to others.

During the movement of contaminants in water, a variety of physical, chemical, and biological processes occur. The above-mentioned processes include solidifying, dissolving, absorption, and desorption from suspended matter; joining with organic and inorganic substances; getting into aquatic organisms; and getting rid of substances from the water by clumping together, precipitating, or sedimenting. As a result, these intricate transportation mechanisms have a significant influence on the presence of contaminants, particularly heavy metals, in water.

There is a strong link between the distribution of heavy metals in water and sediment. Places with lower levels of heavy metals in the water tend to have lower concentrations of sediment compared to other places.

The predominant composition of the silt located in the lower Thi Vai River can be attributed to the process of excavation and modifications occurring inside the Dong Nai River Delta. The sediments under consideration are derived from historical delta formations and are conveyed and settled in the downstream sections of the Thi Vai River predominantly by tidal streams, functioning as a mechanism for sediment conveyance and deposition. The primary direction of transportation for eroded silt is towards the ocean, with a portion of it subsequently redistributed inland due to the significant influence of strong tidal currents. As a result, it can be observed that during periods of high tide in the lower Thi Vai River, there is a minimum occurrence of bottom erosion, with silt gradually accumulating instead. In contrast, when the tide recedes, the primary phenomenon that takes place is erosion [28].

In addition, the dredging operations carried out on the Thi Vai River have a crucial function in preserving unobstructed water circulation, augmenting the river's inherent ability to purify itself, and permitting the unimpeded transit of high-capacity vessels that traverse the ports situated along the Thi Vai River. Dredging operations in this area also have an impact on sediment transport patterns.

IV. Conclusions and Recommendations

This study comprehensively evaluates heavy metal contamination in the downstream segment of the Thi Vai River, concentrating on the distribution of metals in dissolved, suspended particulate matter (SPM), and sediment phases. The findings indicate that Fe and Mn are the predominant heavy metals in all phases, with logKd values surpassing 3, signifying a robust affinity for suspended particulate matter (SPM). The research underscores the substantial impact of industrial operations on elevated metal concentrations, especially in proximity to discharge locations. GIS-based spatial mapping revealed multiple pollution hotspots, highlighting the necessity of targeted interventions. Although the quantities of most metals comply with Vietnam's national regulatory limitations, cadmium levels in specific areas surpass the allowable standards, presenting possible ecological hazards. The results highlight the necessity for ongoing surveillance and enhanced management of industrial effluents to alleviate the enduring effects of heavy metal pollution in the Thi Vai River basin.

The research has not effectively established the influence of flow on the distribution and transport of contaminants within the study region. Despite a general rise in heavy metal concentrations in downstream sources, a definitive trend of increasing or decreasing pollutant concentrations from upstream to downstream remains elusive. Consequently, their influence has to be evaluated in forthcoming study endeavors.

Appendix

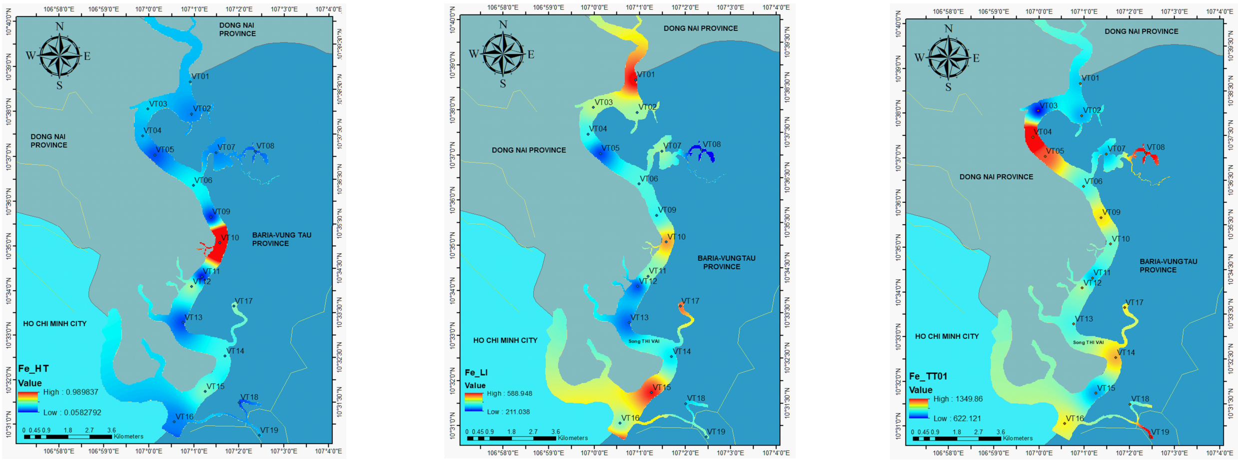

Fig. A1. Distribution of Fe content in the dissolved – suspended – sediment phase.

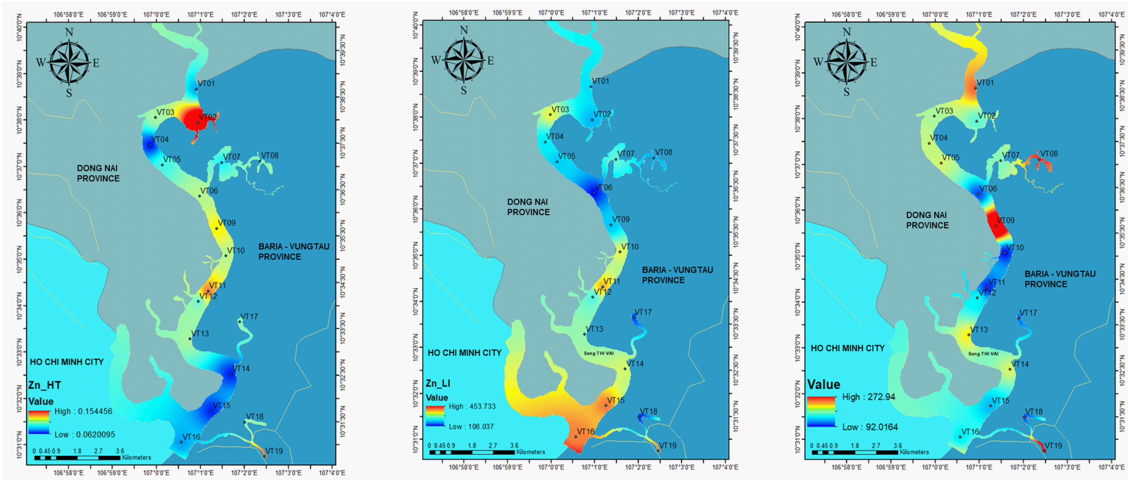

Fig. A2. Distribution of Zn content in the dissolving – suspended – sediment phase.

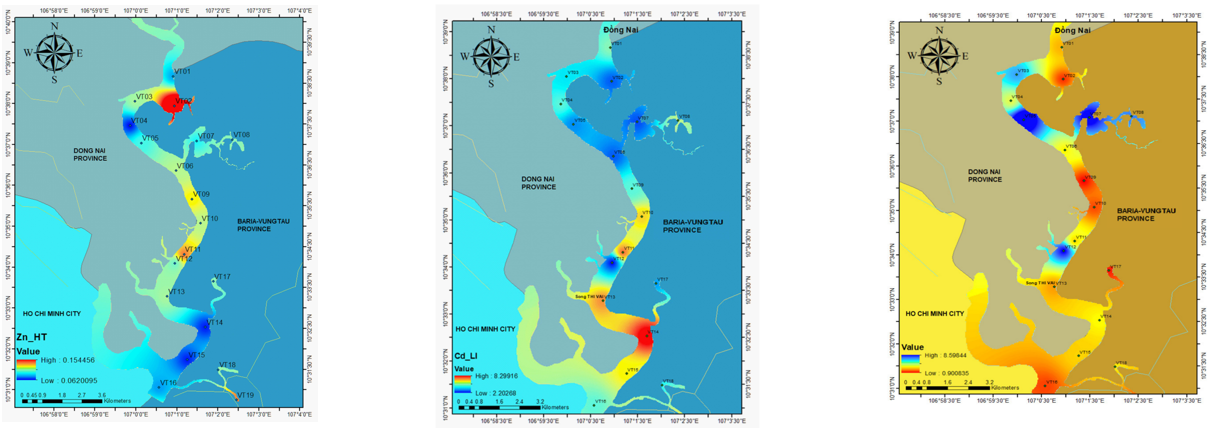

Fig.A3. Distribution of Cd content in the soluble–suspended–sediment phase.

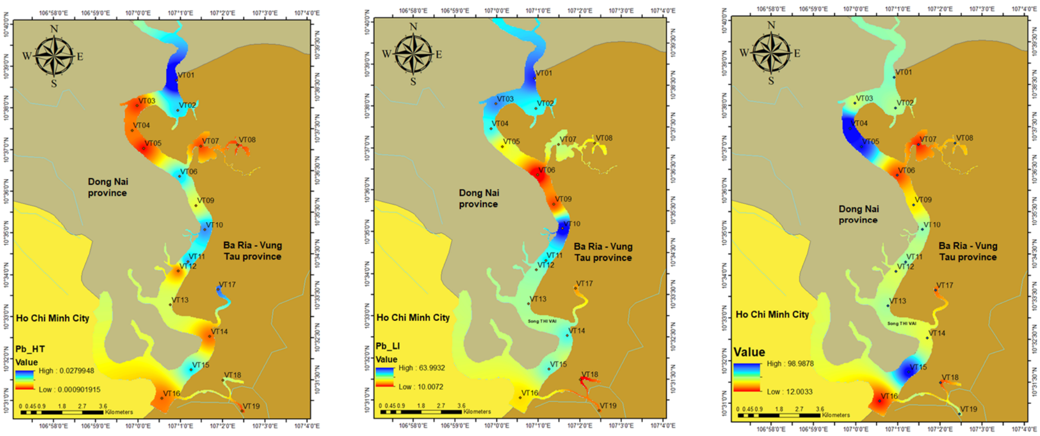

Fig. A4. Distribution of Pb content in the dissolved–suspended–sediment phase

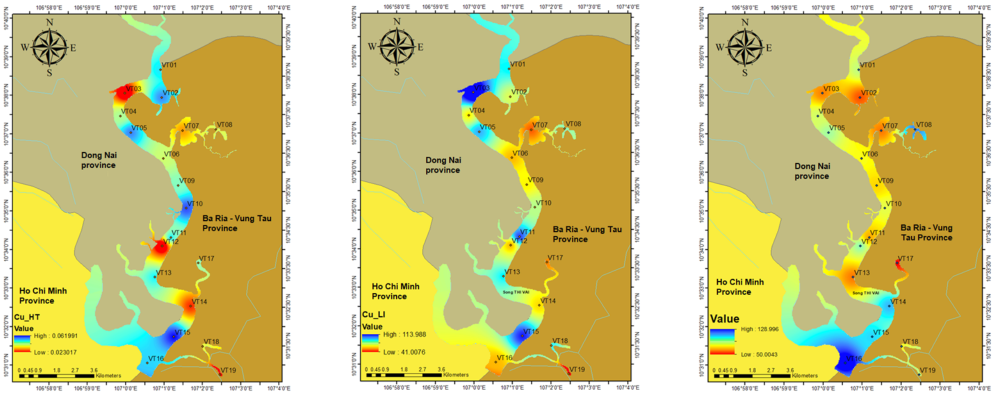

Fig. A5. Distribution of Cu content in the dissolved – suspended – sediment phase

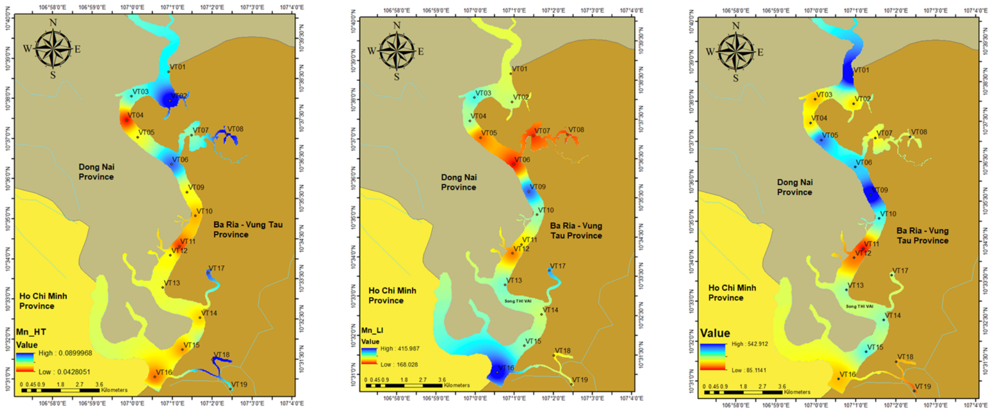

Fig. A6. Distribution of Mn content in the dissolving – suspended – sediment phase

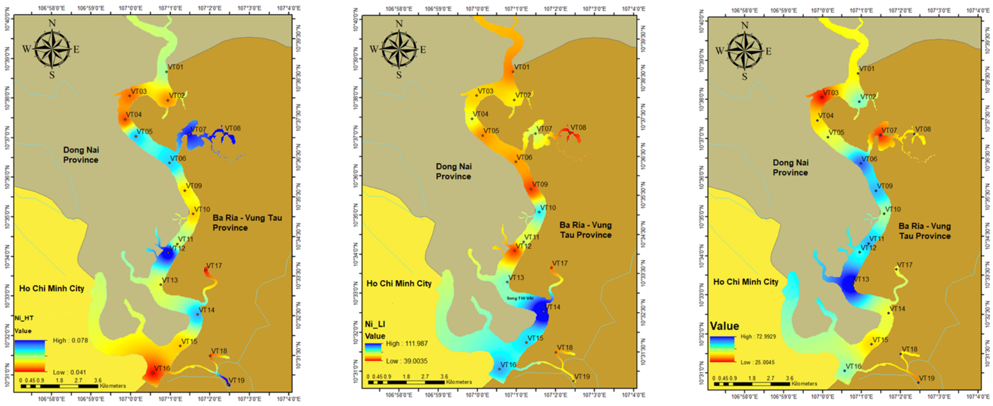

Fig.A7. Distribution of Ni content in the dissolved–suspended–sediment phase

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Au Tinh Thi Nguyen – Conceptualization, methodology, investigation, visualization, writing of the original draft and supervision. Au Hai Nguyen – Methodology, conceptualization, investigation, writing – review, editing and project administration.

Date Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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