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Research Article

Using A Water Quality Index to Assess The Impacts of Heavy Metals Contamination for Sustainable Water Management: A Case Study of the Bang Pakong River, Thailand

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Abstract

Anthropogenic activities such as improper waste disposal, excessive fertilizer use, and industrial effluents cause heavy metal contamination in water, soil, and the atmosphere. Herein, the water quality index (WQI) was used to characterize heavy metal (i.e., cadmium (Cd), arsenic (As), and mercury (Hg)) contamination in the Bang Pakong River, Thailand. Specifically, water samples were collected during the dry season from four stations along the river from 2012–2022. The heavy metal concentrations in the samples were analyzed via atomic absorption spectrophotometry, and WQI values were calculated on the basis of standard water quality parameters. At the four sampling stations, high As concentrations were observed, and the Cd and Hg concentrations were below the detection limits. The WQI values in the 10-year period indicated good water quality on average. However, the WQI values decreased from 2020–2021, followed by a recovery to medium levels in 2022. The WQI reflects heavy metal contamination of local communities in an easy-to-understand manner, revealing its effect on aquatic environments and their health and livelihood.

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Introduction

Among the various sources of water pollution, heavy metals are particularly harmful to ecosystems because of their toxicity, bioaccumulation, environmental persistence, and biomagnification in food chains [1]. Heavy metals are metallic elements with a density higher than that of water. They are naturally present in low concentrations in water and can dissolve in it. Their toxicity to humans and other organisms depends on their form and concentration as well as the exposure pathway.

As, Cd, and Hg are often found in industrial and agricultural effluents discharged into water bodies, leading to contamination. High concentrations of heavy metals in the sediments of water bodies are generally due to anthropogenic activities rather than natural activities [2]. The economic and environmental effects of heavy metal contamination in water and sediments have become a global concern [3].

The Bang Pakong River originates at the confluence of the Prachinburi River and the Nakhonnayok River in Prachinburi Province and passes through Chachoengsao Province over 122 km to meet the Gulf of Thailand. The river flows through four provinces, Prachinburi, Nakhon Nayok, Chachoengsao, Chonburi and 36 subdistricts with 201,858 people living along its banks [4]. The Bang Pakong River has high environmental and social significance in Thailand because of the rich biodiversity of its ecosystem, including freshwater, saltwater, and brackish habitats [5].

The river has approximately 100 aquatic plant species and >400 fish species, including stingrays and small saltwater fishes. Approximately 100 fish species are considered economically relevant. Locals rely on rivers

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and their resources for drinking, aquacultural, and agricultural purposes. However, urbanization and industrialization along the Bang Pakong River are increasing, leading to increasing pollutant discharge pollution into the river and reduced water quality.

Pollution levels in rivers have been increasing annually owing to the lack of water treatment facilities and water being diverted to cities and irrigation systems, reducing the total water discharge and thus the amount of water available to reduce heavy metal concentrations via dilution [4]. Another major source of pollution is the heavy use of pesticides. Owing to water pollution and disease, the number of fish farms in the Bang Pakong River dramatically decreased from over 2,300 in 2000 to only 300–400 in 2009 [5].

Previous literature reported that the Hg and Cd concentrations in the Bang Pakong River were higher than the standards for Thailand and that other heavy metals were within the acceptable range [4]. Similarly, it was reported that As and Hg concentrations were higher than the standards for Thailand for freshwater and marine species. Thailand's Pollution Control Department (PCD) has documented many types of heavy metals and their concentrations over the past decade [6–7].

In addition to these region-specific findings, several studies have used the water quality index (WQI) to evaluate heavy metal contamination in different regions. For example, the WQI has been widely applied to assess heavy metal contamination and water quality conditions. It was used to evaluate groundwater samples in India [8], and to examine the impact of industrial discharge on the Kelantan River in Malaysia [9], to detect heavy metal pollution in surface water in Iraq [10], highlighting its effectiveness as a simple tool for increasing public awareness and environmental decision-making. These studies help demonstrate how the WQI can be used for monitoring and assessing the effects of heavy-metal contamination in aquatic eco-systems.

Understanding the combined effects of various heavy metals on water quality is a complex process, and the effects are often difficult to interpret, particularly for nonexpert audiences. The WQI allows the transformation of complex water quality data into a single value that is easily understood. The WQI combines data on selected heavy metals and water parameters such as temperature, pH, and dissolved oxygen (DO) to determine the overall water quality [11]. The WQI is also useful for researchers, policymakers, and community leaders because it can be used to compare water quality in different areas [11]. Despite several monitoring efforts, no systematic WQI-based assessment integrating heavy metal data and the effect of water contamination on local livelihoods has yet been undertaken for the Bang Pakong River.

This study used the WQI to assess the effects of arsenic, cadmium, and mercury contamination in the Bang Pakong River over a 10-year period (2012–2022) and explored its implications for sustainable water resource management. Specifically, the WQI was used to evaluate the previous water quality status determined by the PCD over the period from 2012–2021. The results revealed the current livelihood situation of locals living along the Bang Pakong River.

Materials and methods

1) Water samples and data collection

Figure 1 shows nine sampling stations along the Bang Pakong River from which water samples were collected in January 2022 (the dry season). The sampling stations are surrounded by local communities, bridges, dams, metal manufacturing industries, aquaculture farms, and agricultural land. Table 1 provides the details and land-use types of each sampling station [7]. The following data were collected: As, Cd, and Hg concentrations as well as pH, temperature, and DO. The selected heavy metals are nonessential trace elements that pose toxic risks even at low concentrations [12].

Water samples were collected at each sampling station via the grab sampling technique via 100 mL high-density polyethylene (HDPE) bottles placed at least 10 cm below the water surface. Before sample collection, the bottles were rinsed with distilled water to maintain a constant pH to avoid the effects of evaporation, precipitation, and other relevant physical and chemical phenomena. To preserve the collected water samples, 0.5 mL of nitric acid was added to each bottle, followed by tight sealing and storing the bottles in a 5 °C icebox prior to analysis. The temperature, DO, and pH values at each sampling station were measured on site via portable meters. To measure the DO and pH values, we used a Hanna HI 9147 meter and a Hanna HI 991003 meter, respectively.

The sample bottles were then transported to the laboratory for analysis within 48 hours. The samples were filtered through a 0.45 µm syringe filter, and As, Cd, and Hg concentrations were measured following the standard analysis methods for water and wastewater samples American Public Health Association (APHA) and the American Water Works Association (AWWA) [13]. Heavy metal (As, Cd, and Hg) concentrations were analyzed via atomic absorption spectrophotometry (PerkinElmer AAnalyst 400) following standard analysis methods for wastewater and water samples (APHA, AWWA). The method detection limits (MDLs) for Cd, Hg, and As were 0.005, 0.001, and 0.005 mg L^{-1}, respectively, based on the sensitivity of the atomic absorption spectrophotometry (AAS) method used in this study. These values are dependent on the detection thresholds referenced in the PCD guidelines. Secondary data on heavy metal concentrations and their effects on the fishery sector were collected from the PCD website and previous studies conducted from 2012–2022.

2) Determination of the WQI

WQI assessment provides a standard method for comparing the surface water quality of various sample types, including river water samples [11]. Table 2 lists the water quality statuses corresponding to various ranges of WQI values according to the National Sanitation Foundation [14].

In this study, the weighted arithmetic WQI was calculated as follows [14]:

(1) Collecting data on various physicochemical water parameters and heavy metal concentrations

(2) Calculate the proportionality constant k:

$$k = 1/(\sum 1/S_n) \quad \text{(Eq.1)}$$

where S_n is the permissible limit for parameter n.

(3) Calculate the quality rating Q_n for parameter n:

$$Q_n = 100\,\{(V_n - V_0)/(S_n - V_0)\} \quad \text{(Eq.2)}$$

Where V_n is the estimated value of parameter n at a given sampling station, V_0 is the ideal value of parameter n in pure water, and S_n is the permissible limit of parameter n.

(4) Calculate the unit weight W_n for parameter n:

$$W_n = k/S_n \quad \text{(Eq.3)}$$

(5) Calculate the WQI:

$$WQI = 1/(\sum W_n * Q_n/\sum W_n) \quad \text{(Eq.4)}$$

Microsoft Excel was used to record the collected data and calculate the WQI.

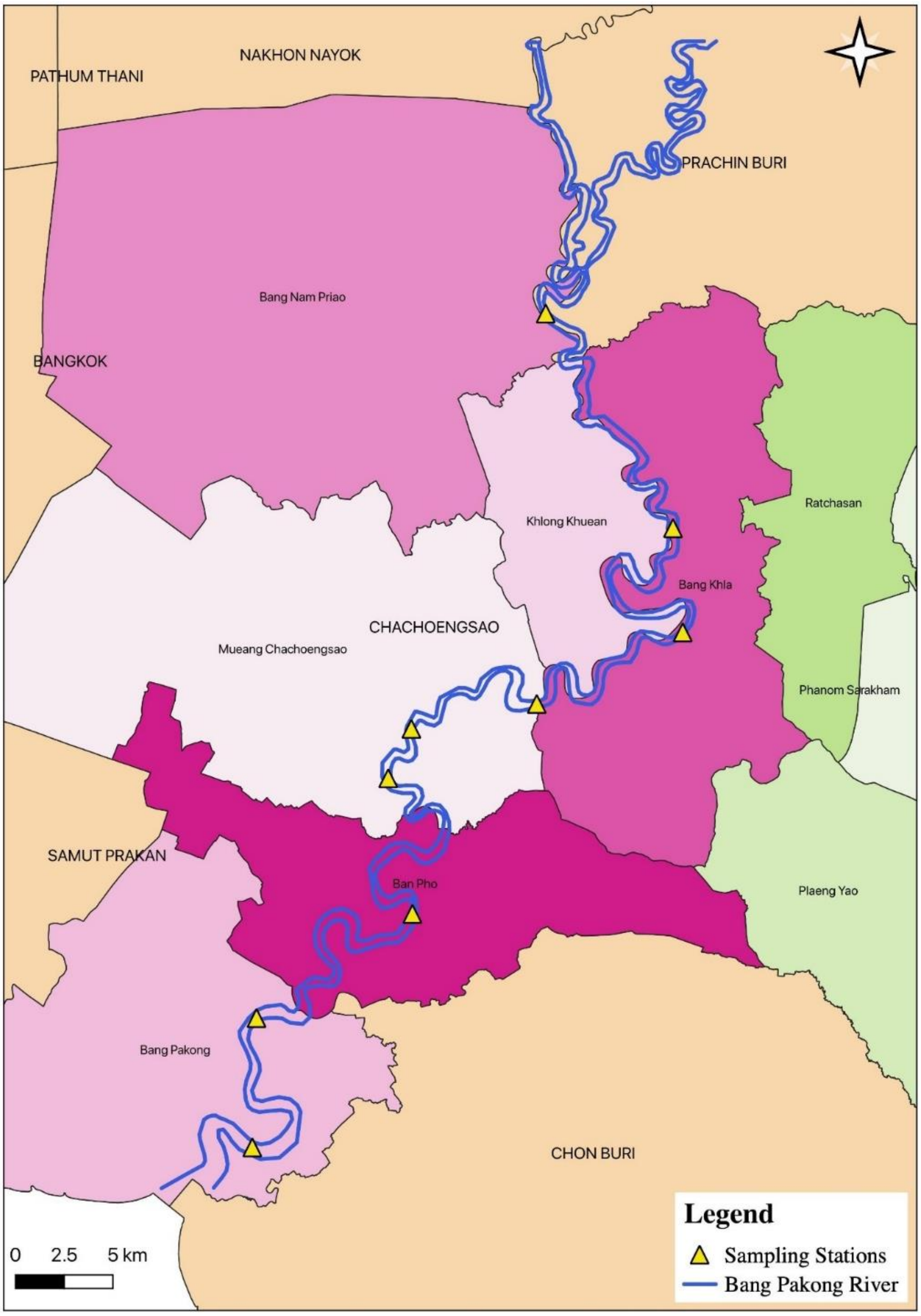

Figure 1 Nine sampling stations along the Bang Pakong River.

3) Surveys for data collection

Surveys were conducted for two purposes: (i) to explore the knowledge and understanding of the local community regarding the ecological conservation of the Bang Pakong River and the effect of water quality on the fishery sector and (ii) to identify the challenges, needs, and satisfaction levels of locals who rely on the aquatic resources of the Bang Pakong River. All procedures were performed in compliance with relevant laws and institutional guidelines and were approved by the Research Ethics Review Committee. To protect the rights of survey participants and maintain data confidentiality, the personal information of the participants was safeguarded. The results were expressed as graphs, charts, and pictures, and they did not identify any individual participants. In addition, personal data collected via questionnaires were destroyed after the completion of this research, and data collected through interviews and discussions were used only for study purposes.

Key informant interviews were carried out with stakeholders who were knowledgeable regarding the conditions of the Bang Pakong River and the negative effects of heavy metal contamination in Chachoengsao Province. In particular, three executives of the fisheries department, two staff members of the natural resources and environment department, two staff members of the coastal aquaculture research and development department, and two members of the local community who were dependent on the river and its aquatic resources were interviewed.

Table 1 Locations of the sampling stations and land-use types along the Bang Pakong River

Stations	Name	Land-use types
BK01	Bang Pakong Bridge, Chachoengsao Province	Industrial estate, Agriculture, Livestock (Pigs and Poultry), Aquacultural farms
BK02	Motorway Bridge, Tha Sa-an Bang Pakong, Chachoengsao Province	Industrial estate, Commercial areas, Households, Agriculture, Livestock (Pigs and Poultry), Aquacultural farms
BK03	Ban Pho District Bridge, Ban Pho, Chachoengsao Province	Industrial estate, Commercial areas, Households, Agriculture, Livestock (Pigs and Poultry), Aquacultural farms
BK04	Bypass Bridge Ban Bang Phra	Industrial estate, Commercial areas, Households, Temples, Agriculture, (Pigs and Poultry), Aquacultural farms
BK05	Bang Pakong River Chachoengsao Bridge	Industrial estate, Commercial areas, Urban areas, Agriculture, (Pigs and Poultry), Aquacultural farms
BK06	Bang Pakong Dam, Khlong Chuk Kracher A. Muang, Chachoengsao Province	Industrial estate, Commercial areas, Households, Agriculture, (Pigs and Poultry), Aquacultural farms
BK07	Amphoe Bangkla Pier Bang Talat Bangkla	Industrial estate, Commercial areas, Urban areas, Agriculture, (Pigs and Poultry), Aquacultural farms
BK08	Wat Hua Sai, Hua Sai, Bang Kla, Chachoengsao Province	Industrial estate, Commercial areas, Households, Agriculture, (Pigs and Poultry), Aquacultural farms
BK09	Bang Kanak Bridge, Bang Kanak Bang Nam Sour, Chachoengsao Province	Industrial estate, Commercial areas, Households, Agriculture, (Pigs and Poultry), Aquacultural farms

Table 2 Water quality index and corresponding status [11, 15]

WQI range	Water quality status	Definition
90–100	Excellent	No harmful substances (pollutants) in water. Required substances like oxygen and other nutrients are present.
70–89	Good	Water quality guidelines are rarely exceeded, but the margin is narrow. Required substances like oxygen and other nutrients are present. Conventional treatment is needed. Appropriate for aquaculture and recreation purposes like swimming.
50–69	Medium	Water quality guidelines are sometimes exceeded. Water cannot be used for drinking without advanced treatment. Treatment is necessary for other purposes like agriculture or households. Appropriate for fishery and domestic animals.
25–49	Bad	Water quality guidelines are often exceeded. Water cannot be used for drinking purposes. Treatment is required for other purposes like agriculture or households. Appropriate for irrigating agricultural land.
0–24	Very bad	Contains harmful substances. Water cannot be used for drinking and other purposes.

Table 3 General information of the interviewees from Chachoengsao Province

No.	Actor	Participants	No. of person
1	Government organizations	Fisheries Department in Chachoengsao Province	3
		Natural Resources and Environment Management in Chachoengsao Province	2
		Coastal Aquaculture Research and Development in Chachoengsao Province	2
2	Local community	Fishermen	6
		Agricultural farmer	3
		Shrimp farmer	3
		Boat driver	1
		Fish seller/Business owner	3
		Private company employee	1
		Student	1

A focus group discussion was conducted with 18 members of the local community who have been continuously living near and relying on the resources of the Bang Pakong River for at least the past 10 years. As listed in Table 3, the members of the focus group were selected on the basis of their occupation and residential area along the Bang Pakong River. In particular, members living near the river mouth were selected because this area has many industries, such as natural gas power plants, manufacturing factories, and agriculture hubs. Other members included fish sellers, urban residents, and workers from restaurants and floating markets at Ban Pho Port [5]. The focus group members were given questionnaires to determine their awareness of the water quality of the Bang Pakong River, contamination by heavy metals, its effect on the fishery sector, and the importance of sustainable development.

Results and discussion

1) Heavy metal concentration

Table 4 presents the current water quality status (2022) of the Bang Pakong River recorded at the sampling stations during the dry season. The Cd, As, and Hg concentrations were within permissible limits according to the PCD standards. The As concentrations were higher at the downstream stations (BK01, BK02, BK03, and BK04) than at the other stations. This was likely due to various manufacturing activities, such as the production of steel plates, vehicle components, building materials, electric equipment, plastics, and furniture, as well as activities related to rice cultivation in the downstream region [16]. In particular, BK01 and BK02 are near the estuary, which contains salt farms, croplands, and other agricultural land. Furthermore, BK03 and BK04 are located along the mainstream Bang Pakong River, which has rice paddies and aquaculture farms [17]. Thus, higher As concentrations in the downstream region were attributed to effluents from point and nonpoint pollution sources located upstream.

A comparison of the dry-season heavy metal concentration results obtained in this study and the PCD data for 2021 (Table 4) revealed no statistically significant differences in the Cd and Hg concentrations. In the wet season, the mean Cd concentration was 0.00165 ±0.00049 mg L^{-1}, while the Cd concentrations at all the sampling stations during the dry season were below the MDL of 0.005 mg L^{-1}. Similarly, the average Hg concentration in the wet season was 0.00157±0.00066 mg L^{-1}, and only one station recorded a detectable value (0.0006 mg L^{-1}) in the dry season. The Hg concentrations at the other stations fell below the MDL of 0.001 mg L^{-1} in the dry season. However, a paired t test revealed that the As concentration was significantly lower in the wet season (0.00196±0.00052 mg L^{-1}) than in the dry season (0.00378±0.00212 mg L^{-1}) ($p<0.05$). It was reported high As concentrations of >0.48 mg kg^{-1} in freshwater fish species of Thailand, such as striped snakehead fish, red tilapia, and Nile tilapia [18].

Therefore, the high As concentrations along the Bang Pakong River were attributed to anthropogenic activities such as urbanization, industrial wastewater discharge, and chemical fertilizer usage on agricultural land. If the Bang Pakong River experiences further urbanization and industrialization, other land-use activities may contribute to other heavy metals and increase the Cd and Hg concentrations to levels similar to those of the As concentration [19]. Table 5 presents the comparison of heavy metal (Hg, Cd, and As) concentrations in the Bang Pakong River and other rivers.

2) Historical water quality status (2012-2022) on the basis of the WQI

Table 6 presents the WQI values of the Bang Pakong River over the 10-year period [4]. The WQI values indicated that the Bang Pakong River generally had excellent and good water quality from 2012–2019, excluding 2013, which had medium water quality. Moreover, the WQI values of the water samples collected at the sampling stations in 2022 ranged from 42.87–58.29, indicating medium quality. The average WQI value for the 10-year period was 80.6, which indicated good water quality. However, the WQI values fluctuated annually, particularly in 2020, 2021, and 2022. In 2022, the WQI value was 50.23, indicating medium water quality.

As presented in Table 2, the medium water quality data suggested that some water parameters exceeded their permissible limits. Water of this quality is not suitable for drinking and requires treatment before being used for agricultural or household activities. For drinking purposes, advanced treatment is necessary. Water of medium quality is suitable only for fisheries, waterway transportation, and as a drinking source for domestic animals. The WQI values determined in the current study were obtained during the dry season. It was evaluated the Bang Pakong River via the Scottish WQI, which they adapted for tropical environments [17]. They observed differences in the WQI values across seasons, with average values of 48% during the wet season and 63% during the dry season. In contrast, the results revealed that only 2.5% of the stations presented lower WQI values in the dry season, whereas 27% presented a decline in the wet season, indicating greater water quality degradation during wetter periods.

While the WQI values in 2022 indicated medium water quality, they were close to the range indicating poor water quality. Figure 2 shows a declining trend in the WQI, particularly between 2020 and 2022. This deterioration was attributed to intensified anthropogenic activities along the Bang Pakong River basin, including agricultural runoff, urbanization, and industrialization. Industrialization and urbanization have increased water utilization and the discharge of untreated or partially treated effluents containing heavy metals into rivers [16]. Additionally, land-use changes such as the expansion of aquaculture farms and the conversion of wetlands into settlements might have exacerbated nonpoint pollution sources during this period.

One of the major problems influencing the hydrological and ecological balance of the Bang Pakong River is the Bang Pakong Dam, which was constructed in 1999 at the center of the river basin (BK06) and was intended to prevent seawater intrusion and to store freshwater for use in the dry season. However, the Bang Pakong Dam has slowed the natural flow of water and has adverse effects on water quality through the accumulation of heavy metals and organic pollutants in sediment and waterways [5]. These factors likely contributed to the decrease in the measured WQI in recent periods. It was reported that water insecurity and the WQI of surface water around Dhaka city were critically discussed; however, there is a need for integrated water resource management (IRWM) strategies [20].

This study revealed that another problem affecting the ecosystem of the Bang Pakong River was floating water hyacinths, which obstruct the flow of water from upstream to downstream and increase the heavy metal concentrations in river water and sediments. The downstream areas of the river receive nutrient-enriched discharge that flows down the river from land-based activities [5]. It was reported that water hyacinths degrade water quality, obstruct transportation, and impair the survival and reproduction of aquatic species in the Bang Pakong River [21].

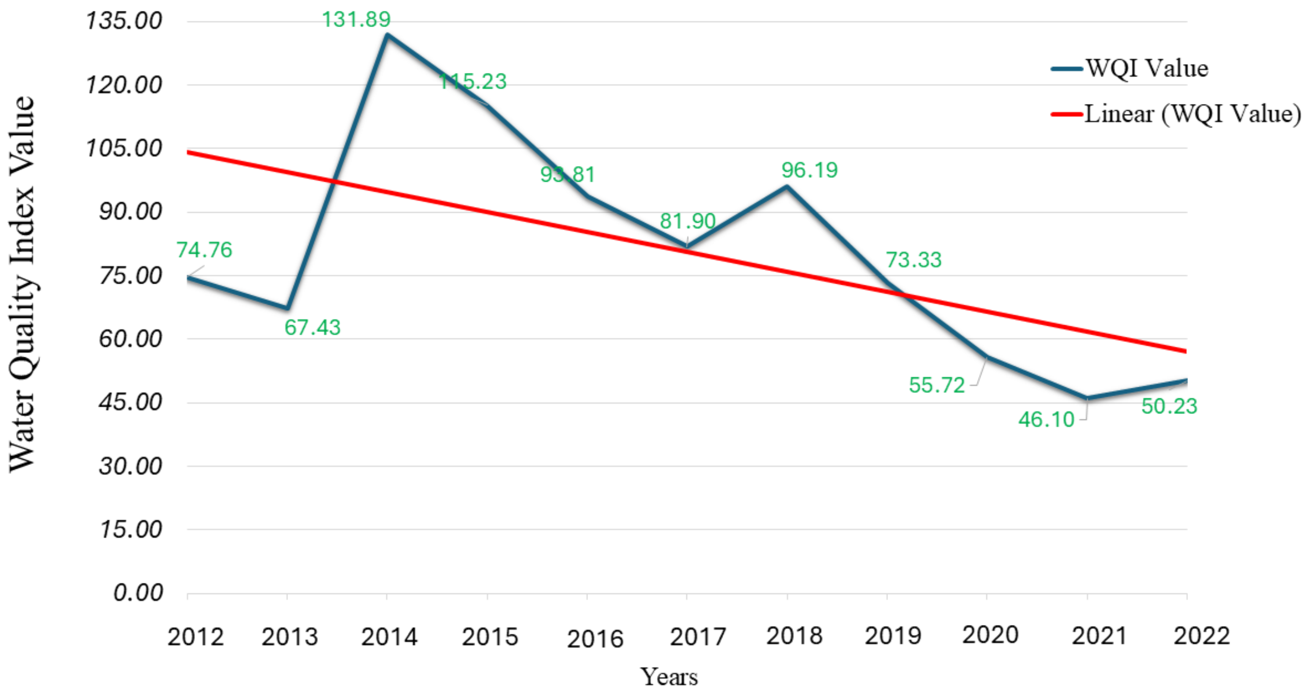

Figure 2 Comparison of average WQI values for the Bang Pakong River from 2012–2022.

Table 4 Physicochemical parameters and heavy metal concentrations in the Bang Pakong River during the wet and dry seasons (2022)

Parameters	**Season**	**BK01**	**BK02**	**BK03**	**BK04**	**BK05**	**BK06**	**BK07**	**BK08**	**BK09**	**PCD Standard**
Temp	Dry	24.0	26.0	27.0	30.0	30.0	32.0	33.0	34.0	34.0	Natural
	Wet	30.7	30.7	31.2	31.3	31.2	31.1	30.7	30.5	30.4	Natural
pH	Dry	7.25	7.27	7.28	7.23	7.26	7.42	7.66	7.58	7.31	9
	Wet	7.4	7.3	7.4	7.2	7.3	7.5	7.5	7.5	7.4	9
DO (mg L^{-1})	Dry	3.95	3.2	3.98	3.39	3.3	3.06	4.56	4.73	4.57	6
	Wet	5.6	3.7	4.2	4.7	4.9	6.9	5.8	5.6	5.4	6
As (mg L^{-1})	Dry	0.008	0.007	0.005	0.004	0.002	0.003	0.002	0.002	0.001	0.001
	Wet	0.0023	0.002	0.002	0.003	0.002	0.0014	0.002	0.002	0.001	0.001
Cd (mg L^{-1})*	Dry	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.005
	Wet	0.002	ND	ND	ND	ND	0.0013	ND	ND	ND	0.005
Hg (mg L^{-1})*	Dry	ND	ND	ND	ND	ND	ND	ND	ND	0.0006	0.005
	Wet	0.0023	ND	ND	ND	ND	0.0014	ND	ND	0.001	0.005

Remark: *The Cd and Hg concentrations were below the MDL at all the sampling stations.
ND = Not detected
Dry-season data were collected by the authors in 2022. Wet-season data were obtained from Thailand's PCD.

Table 5 Comparison of heavy metal (Hg, Cd, and As) concentrations determined in this study and other studies mentioned in the literature

Rivers	Concentration range ($\mu g\ L^{-1}$)	Reference
Mercury (Hg)		
Bang Pakong River, Thailand	0.5 (0.0005 ($mg\ L^{-1}$))	This study
Bang Pakong River, Thailand	0.003	[4]
Bang Pakong River, Thailand	0.135	[22]
Mae Klong River mouth, Thailand	0.104	[22]
Tha Chin River mouth, Thailand	0.154	[22]
Chao Phraya River mouth, Thailand	0.129	[22]
Songkhla Lake (Outer Lake), Thailand	0.049	[23]
Mandovi Estuary, India	0.008	[24]
Danshuei River Estuary, Taiwan	0.024	[25]
Coastal watersheds along the Bohai Sea and Yellow Sea, China	0.95	[26]
Yangtze River Estuary, China	0.036	[27]
Cadmium (Cd)		
Bang Pakong River, Thailand	0.4 (0.0004 $mg\ L^{-1}$)	This study
Bang Pakong River, Thailand	0.13	[4]
Mae Chaem River, Chiang Mai, Thailand	0.33	[28]
Chao Phraya River, Thailand	0.029–0.193	[29]
Yangtze River Estuary, China	0.130	[27]
Bang Pakong River, Thailand	0.12	[21]
Chao Phraya River, Thailand	0.16	[21]
Tha Chin River, Thailand	0.17	[21]
Mae Klong River, Thailand	0.16	[21]
The Gulf of Thailand	0.11	[21]
Arsenic (As)		
Bang Pakong River, Thailand	4.0 (0.004 $mg\ L^{-1}$)	This study
Bang Pakong River, Thailand	8.66	[19]
Mae Klong River, Thailand	7.13	[19]
Tha Chin River, Thailand	8.02	[19]
Mae Chaem River, Chiang Mai, Thailand	32.5	[28]
Inner Gulf of Thailand	7.46	[19]
Songkhla Lake System, Thailand	5.1–25.7	[23]
Yangtze River Estuary, China	1.94	[27]
Brahmaputra River, India	14	[30]
East Kalimantan, Indonesia	2.00	[31]
Thale Noi, Thailand	5.7–10.8	[23]
Bohai Sea, China	3.4–13.6	[27]

Table 6 Average WQI values and corresponding statuses of the Bang Pakong River from 2012–2022

Year	Average WQI	Surface water quality status
2012	74.76	Good
2013	67.43	Medium
2014	131.89	Excellent
2015	115.23	Excellent
2016	93.81	Excellent
2017	81.90	Good
2018	96.19	Excellent
2019	73.33	Good
2020	55.72	Medium
2021	46.10	Bad
2022	50.23	Medium
Average	80.6	Good

3) Impact of heavy metal concentrations on the livelihood of local people

Local residents in Chachoengsao Province depend on the resources of the Bang Pakong River for their livelihood in various ways, such as fishing, agriculture, aquaculture, and driving boats. The production of wetland resources such as *Nypa* palms and salt is the primary economic activity in the Bang Pakong River Basin [5]. Consequently, contamination of the Bang Pakong River by heavy metals can have a ripple effect on the environment and society. The mainstream contains approximately 100 fish species and at least 28 species of water plants, including some that are vulnerable and endangered [32].

According to the survey data of this study, local residents are concerned that some fish species in the Bang Pakong River have gone extinct, which may be at least partially attributed to pollution from wastewater discharged by nearby industries. The local residents who participated in the focus group discussion reported that catching sufficient fish for their livelihood has become increasingly difficult. One fisherman stated, *"I used to catch 10 kilograms a day without much effort. Now I am lucky if I get even 2 or 3 kilograms."* This decrease in fishing stock has directly affected the income of local fishermen. Another participant said, *"Fishing alone is no longer enough to support my family; we have had to take up extra jobs to survive."* These consequences highlight how decreasing water quality and reducing fish stocks have degraded habitual livelihoods in the Bang Pakong River basin. Furthermore, it was reported that the quantity and quality of aquatic species in the Bang Pakong River have been declining, which has directly affected the income of fishermen [32]. Since 2009, local people have been concerned about water contamination and shortages in different seasons as well as the decrease in the stock of some aquatic species, especially fish [5].

Although heavy metal contamination and water pollution likely play significant roles in declining fish populations, other potential factors, such as climate variability, invasive species, and overfishing, should also be considered when investigating this phenomenon. In the present study, the determined WQI values indicated that the Bang Pakong River had medium water quality in 2022 owing to wastewater discharged from industries, which adversely affected the fishery sector. Table 7 summarizes the survey responses of the local community, which demonstrates the socioeconomic effect of decreasing water quality on the fishery sector. The effect can spread to other sectors if no countermeasures are undertaken to protect and manage the river ecosystem.

To better reflect the potential risks and environmental issues associated with the measured heavy metal concentrations, Table 5 shows the results of this study and those obtained for other rivers and estuarine systems within Thailand and around the world. The Hg concentration in the Bang Pakong River measured in this study (0.0005 mg L^{-1}) was considerably lower than previously reported concentrations [4, 22]. Additionally, other major rivers and estuarine regions in Thailand have experienced similar phenomena. These results suggest a possible reduction in Hg contamination over time or spatial differences in pollution sources.

Compared with those in international regions such as the Bohai Sea in China and the Danshuei River estuary in Taiwan, the heavy metal contamination measured in the Bang Pakong River is relatively low, which may be due to effective pollution control, natural dilution, or decreased industrial discharge. The concentration of Cd measured in this study (0.4 μg L^{-1}) slightly exceeded some previously reported values for the Bang Pakong River [4, 21]. However, the concentration remained lower than that reported for the Chao Phraya River and Mae Chaem River. These variations might be due to differences in seasons during sampling, hydrological agricultural activities across regions.

The As concentration measured in this study (4.0 μg L^{-1}) was lower than previously reported values for the Bang Pakong River [19] but comparable to the concentrations measured in rivers across East Asia and Southeast Asia, including China, Indonesia, and India. These results imply that, in the regional context, As contamination in the Bang Pakong River is not abnormally high. Although the heavy metal concentrations determined in this study were within the regulatory limits of Thailand, they should not be neglected. Prolonged exposure to heavy metals, even at low levels, can lead to bioaccumulation and risks to aquatic organisms and human communities, especially locals, who rely on rivers for aquacultural, fishing, and domestic purposes. Therefore, comparing these insights with those from previous studies is pivotal for guiding existing contamination monitoring efforts and effective water quality management policies.

Conclusions

In this study, the WQI was employed to investigate heavy metal contamination in the Bang Pakong River. High As concentrations were observed at some sampling stations, indicating water quality reduction and risks to aquatic ecosystems. Focus group discussions with locals revealed increasing difficulties in relying on river resources for their livelihoods, largely due to increasing urbanization and industrialization in the region. This study provides essential baseline data for mitigating and controlling heavy metal contamination in the Bang Pakong River. The observed heavy metal concentrations at the sampling stations can inform land-use planning and guide future urban expansion in Chachoengsao Province.

Table 7 Survey responses of the local community on the effects of heavy-metal contamination on Bang Pakong River

Usage purposes	Problems or concerns	Possible pollution sources	Struggles and barriers	Suggestions to protect the fishery sector
Fishing, transportation	Municipal waste (garbage, wastewater)	Waste effluent from factories	Declining fish catching rate has affected the income of local residents	Reduce or treat wastewater discharged from factories
Drinking water, fishponds, watering plants, cultivation	Poor water quality, mortality of fish species, loss of biodiversity	Wastewater from factories, households, markets, and communities	Additional jobs needed and changing careers to no longer rely on river resources	Reduce sedimentation of river
Various occupations	Garbage, water hyacinths, sediments, and wastewater from factories reduce water depth and increasing erosion	Saltwater intrusion	Local residents need to find an extra job to increase income	Promote controlled aquaculture farming
Cultivation	Wastewater discharge has killed shrimp	Bang Pakong Dam is the biggest problem	Decreased water quality makes it difficult to drink water and earn income from fishing	Control release of municipal wastewater
Aquaculture	Water conditions in the future are likely to deteriorate because of increasing contamination	Large number of chemical substances discharged from agricultural land	Fewer fish leading to career change	Control the extinction of aquatic species
Agriculture, gardening, aquaculture	Increased free-floating water hyacinths in the river causing difficulty with waterway transportation and survival of other aquatic species	Wastewater released by the private sector	Shrimp and fish catches have decreased from previous years. Income has dropped dramatically. Fishing equipment is expensive, but fish are sold at low prices	Remove sediment from the river to facilitate waterway transportation
Consuming fish and other aquatic animals	Aquatic life and species are still abundant, but some species are no longer found	Large amounts of garbage in the river may be toxic	Difficult to farm fish	Address water and atmospheric pollution that has affected water quality
Consumption, cultivation	Chemical contamination	Wastewater discharged from an upstream brewery	Shortage of fresh water	Supporting more freshwater fish species
Transportation, fishing	Insufficient water due to poor water quality and reduced water depth	Riverbank erosion may result in fewer aquatic animals	Changing careers to boat driver because of better earning potential	Limit fishing to a certain period each year
Aquaculture	Increased pollution, low water levels in the dry season, poor water quality	Bang Pakong Dam may harm the spawning of aquatic species	Fewer fish species and less income	Check the water quality monthly and inform the public of the status

The WQI serves as an effective tool for communicating water quality variations to local communities, particularly fishermen. In the future, WQI-based awareness programs and citizen science initiatives can be developed to support public understanding of water pollution risk, the influence of water quality on the aquatic environment, and related health and livelihood distress. For example, simplified WQI dashboards or mobile alert systems can enable local communities to monitor surface water quality conditions and respond rapidly to pollution incidents. These participatory approaches will contribute to enhanced environmental knowledge of the local community and promote shared responsibility for the conservation of river ecosystems.

To ensure sustainable water management, real-time water quality monitoring systems should be implemented, particularly in areas with high industrial discharge. Pollution control policies should be strengthened for areas near critical discharge points, and community-driven initiatives for river restoration should be undertaken. Furthermore, regional collaboration among local authorities, residents, and industry stakeholders should be sought to promote participatory water management. Future research should incorporate long-term water quality monitoring and integrated ecological assessments to better understand the cumulative effects of pollution and contribute to adaptive river basin management.

In Thailand, internet-of-things-based water quality sensors (e.g., those used for monitoring pH, DO, or heavy metal concentrations) that provide real-time data via mobile networks can be employed. Furthermore, satellite data obtained from the Geoinformatics and Space Technology Development Agency can be used to monitor surface water dynamics. Integrating these technologies will help develop early warning systems, provide data for policy making, and allow institutions and communities to respond effectively to environmental issues.

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