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Research article

Heavy metals loading in tropical urban river: A case of industrial catchment

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Abstract: Heavy metal contamination in industrial areas poses significant environmental challenges due to the lack of early detection and control mechanisms. Typically, remediation actions are taken only once contamination reaches hazardous levels. In this study, we evaluated the distribution of heavy metals in two rivers in Johor Bahru, Malaysia, namely the Selangkah and Kim Kim Rivers, with particular emphasis on concentrations exceeding threshold limits. Our primary objective was to assess the degree of heavy metal pollution and highlight the influence of both point and non-point pollution sources. Key water quality parameters were analyzed, including heavy metal concentrations, electrical conductivity (EC), (pH), salinity (SAL), and dissolved oxygen (DO). The overall mean concentrations of potassium (K), iron (Fe), and magnesium (Mg) were highest in both rivers, with Mg exceeding the permissible limit of 150 mg/L in the Kim Kim River (Maximum concentration recorded: 412.63 mg/L). In the Selangkah River, mean concentrations of copper (Cu) (0.157 mg/L), Fe (4.591 mg/L), and nickel (Ni) (0.493 mg/L) significantly exceeded the maximum allowable limits for surface water set by the Malaysian Ministry of Health and the National Water Quality Standards (NWQS). Spatial distribution identified sampling points SL1, SL4, SL5, and SL6 along the Selangkah River as having the highest concentrations of most heavy metals, correlating with the dense concentration of industrial activities in those areas. The Contamination Index (Cd) and Heavy Metal Pollution Index (HPI) calculations confirmed that the Selangkah River is classified as highly polluted, while the Kim Kim River presents a moderate-to-high pollution status. Given that these rivers support smallholder

agriculture and contribute to groundwater recharge, protecting and conserving their fragile ecosystems is essential to ensure long-term environmental sustainability and public health safety.

Keywords: heavy metals; Selangkah river; Kim Kim river; industrial area; environment quality act 1974; Malaysian national water quality standard; pollution index

1. Introduction

Water is crucial for the growth and survival of all living things and is considered a 'Universal Solvent'. Around 71.0% of the earth's surface area is covered by water, of which 96.5% of the water is found in the seas, 0.9% water is other saltwater, and the remaining 2.5% is freshwater that occurs in ice caps, glaciers, rivers, lakes, ponds, streams, and ground water. Moreover, of 2.5% freshwater, 1.2% is surface water [1]. This reflects just a small fraction of freshwater that occurs in rivers. Additionally, water contains the fundamental ingredients needed for biological reactions to occur throughout metabolic processes. Around 1.6 billion people worldwide experience water scarcity, and two-thirds of the population is affected [2,3]. Water is said to be contaminated when some pollutants enter the river water in large quantities that they render unfit for drinking, bathing, cooking, or other purposes.

However, due to a variety of contaminants generated by humans, this vital natural resource is under severe threats. The occurrence of water pollution is a critical issue that causes many problems in the river ecosystem, alters water quality, and poses effects on aquatic fauna and human health hazards, i.e., cholera, diarrhea, dysentery, and hepatitis [4–7]. The major sources of river water pollutants are inflow of wastewater from domestic sewage, effluent from mining areas, agriculture runoff containing pesticides, and industrial effluents from distilleries, tanneries, pulp and paper, textile, food, and steel industries [8–13]. In addition, river water is polluted from rock weathering and soil erosion [14–16].

River ecosystems have become endangered due to water quality deterioration from deposition of organic and inorganic contaminants from various resources [17,18]. This is because most metals are unable to naturally degrade, and as a result, their toxic effects can persist in the river water and have a harmful impact on aquatic life. Exposure to heavy metals can, either directly or indirectly, result in a number of ailments in humans and aquatic animals, including cancer, kidney damage, life impacts, and retarded body growth that cause death [19–21]. Specifically, non-critical metals, insoluble toxic metals, and toxic metals can be used to categorize metals in the context of river contamination [22].

The extent of polluted water being released into the Selangkah and Kim Kim Rivers in Pasir Gudang, Johor Bahru, which drains into the Straits of Johor and the adjacent sea, is not fully known. Thus, the extent of the aquatic life that has been damaged and poisoned because of the heavy metals effluents into these rivers has not been quantified. To date, no scientific studies have been documented within this industrial catchment area since the major pollution incident in 2019. The absence of prior research highlights the necessity and relevance of this study. Moreover, the methodological approaches and findings presented here offer a valuable foundation for future research and monitoring efforts in similar industrial catchment settings. Thus, we address a critical gap in environmental monitoring by highlighting the inadequate regulation and limited academic focus on heavy metal contamination in industrial areas. The absence of a structured and proactive approach to contamination assessment hampers early detection and timely intervention, leading to reactive measures only after pollutant concentrations reach hazardous levels. Given that alterations in the physicochemical properties of water can severely impact human health and aquatic ecosystems, understanding the spatial distribution and behavior of these contaminants is vital for effective mitigation and long-term ecological protection. Therefore, this study was conducted to determine the concentrations and spatial distribution of heavy metals in the Selangkah and Kim Kim Rivers. Our primary objective is to assess the state of heavy metal pollution by comparing concentrations to Malaysian water quality standards and by calculating established pollution indices, such as the Heavy Metal Pollution Index (HPI) and the Contamination Index (Cd). For this comprehensive assessment, we aim to provide a quantitative measure of the ecological risk and to highlight the influence of industrial activities in this critical urban catchment area.

2. Materials and methods

2.1. Study site

To measure the distribution patterns of heavy metals in Selangkah and Kim Kim Rivers, this study was conducted in the industrial region of Pasir Gudang in Johor, Malaysia (Figure 1). The length of the Kim Kim River is 7.40 km, whereas the Selangkah River is 5.40 km. The average width of both rivers at the sampling locations is approximately 10–20 meters with an average depth of 1–10 meters, characterizing them as shallow urban rivers highly susceptible to pollutant accumulation. Unlike the Kim Kim River, which runs in urban settlements, the Selangkah River runs between heavily industrialized areas such as electrical and electronics, food products, chemical, plastics and engineering-based industries, and commercial areas. Since the past decade, there have been around 252 petroleum refineries at Pasir Gudang that discharged effluent into the Straits of Johor and the coastal areas of the sea.

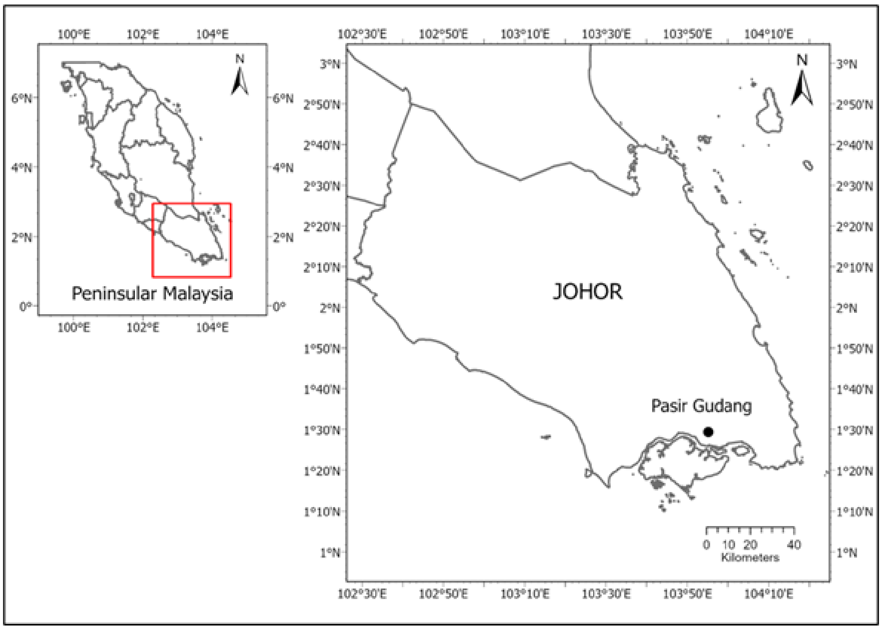


Figure 1. Study location at Pasir Gudang, Johor, Malaysia.

2.2. Water Sample Collections

Six sampling points along the Kim Kim River and thirteen (13) sampling points along the

Selangkah River were selected randomly (Figure 2). Water samples were collected from the same stations over three consecutive months (November 2020 until January 2021). To measure total metal concentrations, the samples were collected and then preserved. To inhibit the growth of mold and algae, 1% (v/v) of 67%–68% concentrated nitric acid (trace metal grade) (Fisher brand) was added to the water samples immediately after collection. The preserved samples were subsequently subjected to an established acid digestion protocol in the laboratory to ensure both dissolved and suspended metal fractions were measured. The water samples were brought to the lab. The solid content was extracted using filter paper (after digestion) and the solution analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (NexIon 350x Model, Perkin Elmer brand). The nebulizer gas flow (argon) for the (ICP-MS) was set to 0.97 L/min, and the RF ICP power was 1400 W.

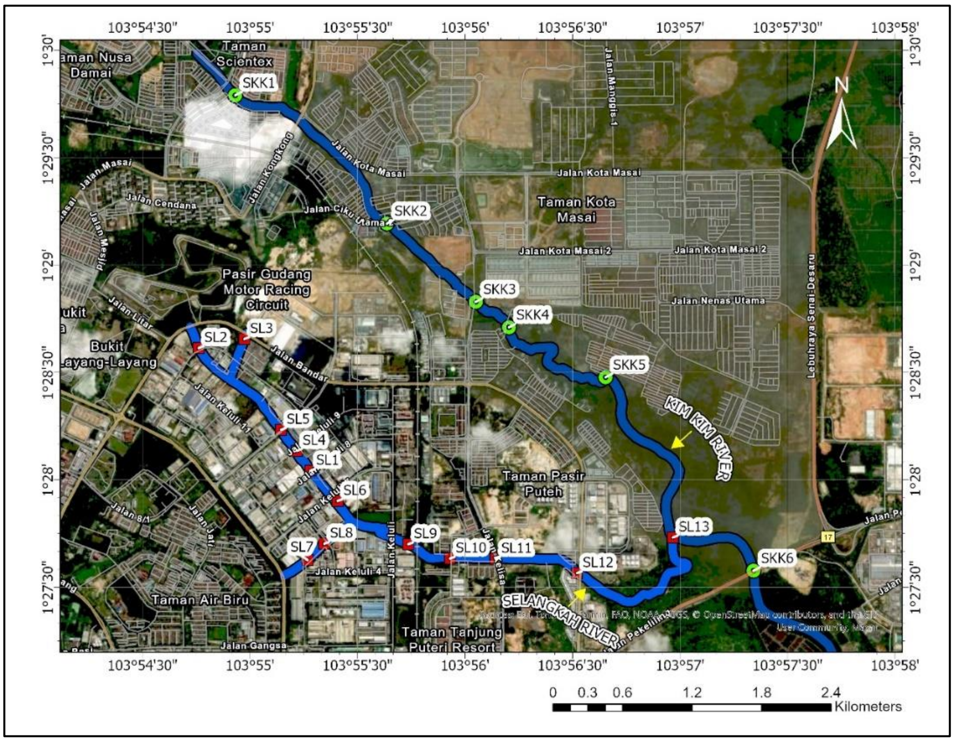


Figure 2. Sampling points at Selangkah and Kim Kim Rivers (Selangkah river denote as SL and Kim Kim river denote as SKK).

2.3. Water sample analysis

Metal analysis was performed on the acid-digested water samples using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The analytical protocol, referred to internally as the Total Quant approach, relies on comparing the measured ion intensity (cps) of the samples against a multi-element reference standard solution to accurately quantify the total metal concentration. A standard solution of 10 ppm, multi-element 1, 2, 3, 4, and 5, was then used to create calibration graphs for each of the element concentrations, i.e., 5 ppb, 20 ppb, 50 ppb, and 100 ppb (Perkin Elmer). The following equation was used to calculate the standard solution's concentration:

$$m1v1 = m2v2, \quad (1)$$

where m1 = the initial concentration, v1 = the initial volume, m2 = the final concentration, and v2 =

the final volume. In addition, each standard graph was created using a linear regression value of 0.998 or close to it (minimum). If any concentrations of an element were outside the linear range, the water sample was diluted with distilled water and 2% nitric acid (v/v) was added. The existence of the following elements in the water samples was also measured: Aluminum (Al), arsenic (As), calcium (Ca), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), lithium (Li), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), strontium (Sr), and zinc (Zn). The procedure was carried out in accordance with the instructions of [23].

2.4. Pollution indices and statistical analysis

To provide a quantitative assessment of the heavy metal pollution status, two widely recognized pollution indices were calculated for both rivers: The Heavy Metal Pollution Index (HPI) and the Contamination Index (C_d).

2.4.1. Heavy metal pollution index HPI

The HPI is a unitless index that provides a cumulative measure of the overall quality of water with respect to heavy metals. It is calculated using the following equation:

$$\text{HPI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (2)$$

where the unit weight W_i is defined as the inverse of the maximum permissible concentration (C_{max}), ensuring that higher C_{max} values are weighted less heavily, calculated as $W_i = 1/ C_{max(i)}$.

The sub-index Qi is calculated as $Q_i = 100 \times [(C_i - I_i) / (S_i - I_i)]$, where C_i is monitored metal concentration, I_i is the ideal concentration (assumed to be zero for most heavy metals), and S_i is the standard value (C_{max}). The critical pollution index value (HPI_{crit}) for water quality is 100.

2.4.2. Contamination index (C_d)

The C_d is a measure of the extent of heavy metal contamination at specific locations. It is derived from the sum of the contamination factors (C_f) of individual metals:

$$C_d = \sum_{i=1}^{n} C_{fi} \quad (3)$$

where C_{fi} is the contamination factor for the i^{th} metal, calculated as the ratio of the mean concentration (C_i) to the maximum permissible concentration (C_{max}) of the i^{th} metal according to NWQS Class IIA limit.

$$Cfi = \frac{C_i}{C_{max}} \quad (4)$$

The C_d is classified as Low (< 1), Medium (1–3), High (3–6), and Very High (> 6). The C_{max} values used for calculation are presented in Table 2 (NWQS Class IIA Limit column).

2.4.3. Statistical analysis

The average values for each element at each station were determined from the three-monthly measurements. All results are presented as the Mean ± Standard Deviation (SD). Furthermore, the minimum (Min) and maximum (Max) concentrations recorded across all sampling events are included to reflect the range of pollutant loading.

3. Results

3.1. Physico-chemical parameters (EC, pH, SAL, DO)

In addition to heavy metals, key physico-chemical parameters were measured in the field to provide context for the aquatic environment (Table 1).

Table 1. Physico-chemical parameters in the Selangkah and Kim Kim Rivers.

Parameter	Selangkah River (Mean ± SD)	Kim Kim River (Mean ± SD)	NWQS Class IIA Limit
pH	6.34–7.78	6.78–7.04	6.0–9.0
Electrical Conductivity (EC, μS/cm)	2383.13 ± 5703.80	5408.25 ± 11533.30	No standard
Salinity (SAL, ppt)	1.32 ± 3.34	3.18 ± 6.93	No standard
Dissolved Oxygen (DO, mg/L)	2.88 ± 1.82	1.51 ± 1.19	≥ 5.0

*Note: pH values are reported as a range (Minimum–Maximum).

The pH ranges in both rivers (6.34–7.78 in Selangkah; 6.78–7.04 in Kim Kim) were within the acceptable NWQS limits (Class IIA). However, the mean Dissolved Oxygen (DO) levels were critically low in both rivers, with the Kim Kim River recording an average of only 1.51 mg/L. These low DO values were significantly below the MNWQS Class IIA limit (5.0 mg/L), suggesting severe organic pollution and high biological oxygen demand. Furthermore, the Kim Kim River exhibited higher mean EC (5408.25 ± 11533.30) and Salinity (3.18 ± 6.93) than the Selangkah River, with the very large standard deviations indicating high temporal variability and the presence of highly concentrated localized sources, likely from tidal influence or untreated wastewater inputs.

3.2. Occurrence of heavy metals in the studied rivers

Our findings revealed that six water samples from the Kim Kim River and thirteen water samples from the Selangkah River indicated the existence of twelve heavy metal elements (Table 2). The concentrations presented represent the mean of three monthly results, along with the calculated standard deviation, minimum, and maximum values. The results demonstrated that the Selangkah and Kim Kim Rivers' water possessed comparatively higher accumulation of the elements K, Fe, Mg, Cu, Ni, and Zn, which were prevalent.

The overall river average concentrations of K, Fe, and Mg were highest in both rivers. In particular, the Selangkah River exhibited high mean concentrations of Cu (0.751 mg/L), Fe (4.251 mg/L), and Ni (1.043 mg/L), all of which exceeded the maximum allowable limits for surface water set by the Malaysian Ministry of Health and NWQS [24]. Moreover, in the Kim Kim River, the highest recorded concentration for Mg (412.63 mg/L) at station SKK6 surpassed the permissible limits of 150 mg/L recommended by the Malaysian NWQS [25].

Table 2. Average concentration (Mean ± SD) of heavy metals in water samples from Selangkah and Kim Kim Rivers, along with Min and Max values, compared to NWQS and MOH standard limits (values highlighted in bold indicate exceedance of Class IIA standard).

Location/ Sampling station/Limit	Concentration (mg/l)											
	As	**Cr**	**Pb**	**Co**	**Cu**	**Li**	**Mn**	**Fe**	**K**	**Mg**	**Ni**	**Zn**
Selangkah River												
SL1	0.0013	0.0490	0.0030	0.0026	**0.7510**	0.0060	0.0510	**4.2510**	23.8300	1.6060	**1.0430**	0.9450
SL2	0.0018	0.0140	0.0030	0.0004	0.0040	0.0030	0.0270	**3.5160**	5.6600	1.4150	0.0090	**2.1620**
SL3	0.0011	0.0200	0.0040	0.0004	0.0040	0.0030	0.0340	**2.7400**	5.3200	1.6100	0.0110	0.1670
SL4	0.0012	0.0090	0.0030	0.0010	0.1200	0.0050	0.0430	**2.1210**	22.6000	1.4230	**0.7280**	0.6800
SL5	0.0011	0.0130	0.0040	0.0005	0.2000	0.0050	0.0380	**6.9000**	20.2700	1.4570	**0.8620**	0.7310
SL6	0.0017	0.0160	0.0040	0.0008	**0.3150**	0.0050	0.0490	**3.4720**	18.9000	1.9290	**0.8610**	0.6930
SL7	0.0022	0.0110	0.0040	0.0004	0.0060	0.0030	0.0350	**9.1170**	7.2200	1.7580	0.0080	0.1600
SL8	0.0022	0.0130	0.0020	0.0004	0.0070	0.0020	0.0390	**9.4490**	7.1900	1.8160	0.0080	0.1350
SL9	0.0015	0.0150	0.0030	0.0009	0.1650	0.0040	0.0370	**3.7660**	16.8000	2.1420	**0.5220**	0.4600
SL10	0.0016	0.0120	0.0050	0.0007	0.1210	0.0040	0.0380	**3.7250**	16.3900	2.3380	**0.4840**	1.0700
SL11	0.0015	0.0130	0.0040	0.0007	0.1460	0.0040	0.0410	**4.4030**	16.7100	2.2520	**0.5440**	0.8900
SL12	0.0016	0.0120	0.0030	0.0006	0.1290	0.0030	0.0440	**4.7120**	13.6700	1.6700	**0.3960**	0.4660
SL13	0.0015	0.0030	0.0020	0.0004	0.0680	0.0050	0.0380	**4.9960**	28.5000	49.6810	**0.2350**	0.3800
Mean	0.0016	0.0154	0.0034	0.0008	0.1566	0.0040	0.0395	4.8591	15.6200	5.4690	0.4393	0.6876
Min	0.0011	0.0030	0.0020	0.0004	0.0040	0.0020	0.0270	2.1210	5.3200	1.4150	0.0080	0.1350
Max	0.0022	0.0490	0.0050	0.0026	0.7510	0.0060	0.0510	9.4490	28.5000	49.6810	1.0430	2.1620
Std	0.0003	0.0104	0.0008	0.0006	0.1928	0.0011	0.0061	2.1870	7.1699	12.7663	0.3517	0.5174
Kim Kim River												
SKK1	0.0012	0.003	0.004	0.0005	0.003	0.0004	0.102	**4.7**	3.03	1.513	0.006	0.411
SKK2	0.0016	0.001	0.002	0.0004	0.003	0.001	0.085	**5.022**	3.82	1.071	0.002	0.317
SKK3	0.0017	0.001	0.003	0.0004	0.003	0.001	0.073	**5.039**	4.02	1.801	0.001	0.908
SKK4	0.0016	0.001	0.002	0.0003	0.003	0.001	0.074	**4.234**	3.91	1.66	0.001	0.403
SKK5	0.0026	0.002	0.002	0.0004	0.003	0.005	0.092	**4.713**	24.24	70.151	0.005	0.213
SKK6	0.0014	0.001	0.001	0.0003	0.003	0.029	0.023	**3.068**	165.41	**412.63**	0.018	0.15
Mean	0.0017	0.0015	0.0023	0.0004	0.0030	0.0062	0.0748	4.4627	34.0717	81.4710	0.0055	0.4003
Min	0.0012	0.0010	0.0010	0.0003	0.0030	0.0004	0.0230	3.0680	3.0300	1.0710	0.0010	0.1500
Max	0.0026	0.0030	0.0040	0.0005	0.0030	0.0290	0.1020	5.0390	165.4100	412.6300	0.0180	0.9080
Std	0.0004	0.0008	0.0009	0.0001	0.0000	0.0103	0.0253	0.6784	59.2143	150.2048	0.0059	0.2458
EQA 1974 (Industrial Effluents) 2009	0.05	0.05	0.1	-	0.2	-	0.2	1	-	-	0.2	2
NWQS (Class 1-V)	0.05-0.4	0.05-0.1	0.05-5	-	0.02-0.2	-	0.1-0.2	1	-	-	0.05-0.9	2-5
MOH (Recommended Raw Water Quality)	0.01	0.05	0.05	-		-	-	1	-	150		3

*Note: The values in bold indicate being above the allowable standard.

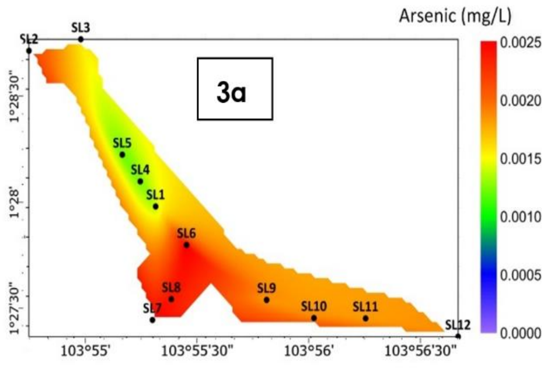
High Fe concentrations in water can cause an unpleasant metallic taste [26]. In this study, the average Fe concentration in water samples from the Selangkah (Mean: 4.2510 mg/L) and Kim Kim Rivers (Mean: 4.4627 mg/L) were significantly above the permissible limits of 1.0 mg/L for raw water recommended by the MNWQS and the Ministry of Health (MOH) of Malaysia.

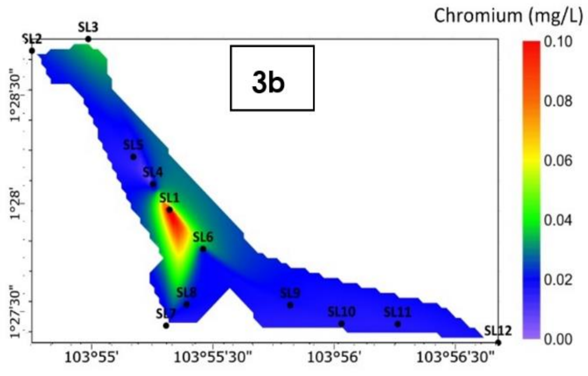
3.3. Selangkah river heavy metals spatial distribution pattern

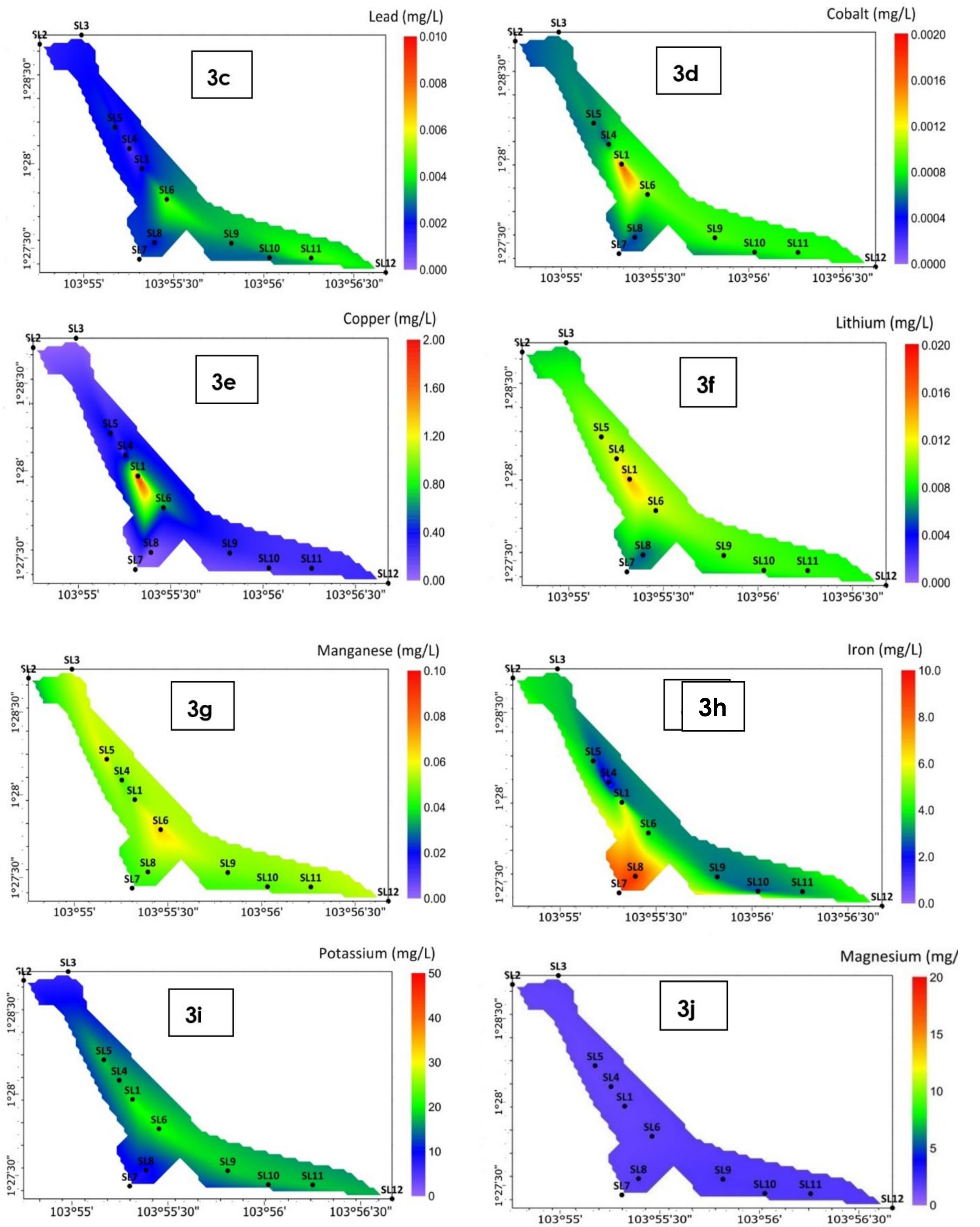
The distribution pattern of heavy metals along Selangkah river were analyzed using the Natural Neighbour approach in Surfer 12. By the preferential accumulation path of As that is released by effluent discharge from nearby factories, the discoveries showed that the high concentration of the As element was detected at SL6 (0.0017 mg/L), SL7 (0.002 mg/L), and SL8 (0.002 mg/L) sampling sites as well as SKK5 (0.0026 mg/L). A high Cr concentration (0.05 mg/L) was discovered at the SL1 sample station, highlighting a major contribution, which was the considerable source effluent that was accumulated between sampling stations SL1 and SL6. However, the distribution pattern of Co and Pb concentrations were consistent, flowing extensively down the Selangkah River at sampling sites SL1 and SL6, as well as from SL9, SL10, SL11, and SL12 (Figure 3a–3l).

Strikingly, the remarkable concentrations of Cu, Li, and Mn elements were encountered at the SL1 and SL6 sampling stations, respectively. The findings revealed that three components were not sparsely dispersed, and as a result, they were likely to locally concentrate into these rivers. In the SL7 and SL8 sample sites near the Selangkah River's tributary branch, the maximum Fe concentrations were found. However equal concentrations of Co, Pb, and K elements were identified in their distribution patterns. At each sampling point, the Mg concentration distribution pattern was consistent throughout. Besides that, Ni and Zn were detected at the highest concentrations in the SL1, SL4, SL5, and SL6 sampling sites (Figure 3a–3l).

Notably, overall heavy metals were detected at SL1, SL4, SL5, and SL6 sites that had greater concentrations of Fe, Ni, and Cu and exceeded the Environmental Quality Act's 1974 upper limit values. Similar to this, higher concentrations of the Fe element were observed at the SL7 and SL8 stations, surpassing the permitted upper limits. The main cause of Fe concentration in river water could be due to the occurrence of heavily inhabited areas with industries that are continually working and releasing effluents into river waters. Additionally, the Selangkah River's SL1 and SL6 sampling sites had significant amounts of As, Cr, Co, Pb, and K elements, as well as comparatively greater accumulations of Cr, Co, Cu, Ni, and Zn elements. However, the excess of As, Cr, Co, Pb, K, and Zn in surface water did not surpass the highest permissible limits (Figure 3a–3l).






3c
Lead (mg/L)
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Copper (mg/L)
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Potassium (mg/L)
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Magnesium (mg/
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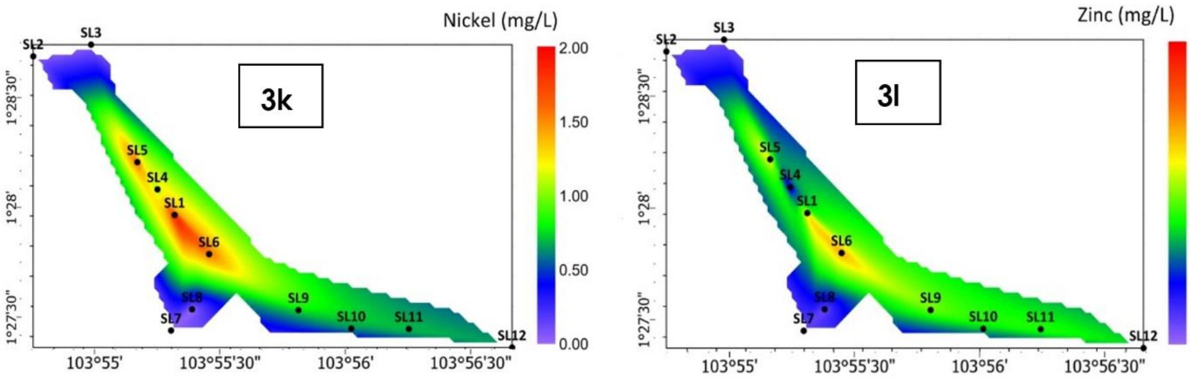


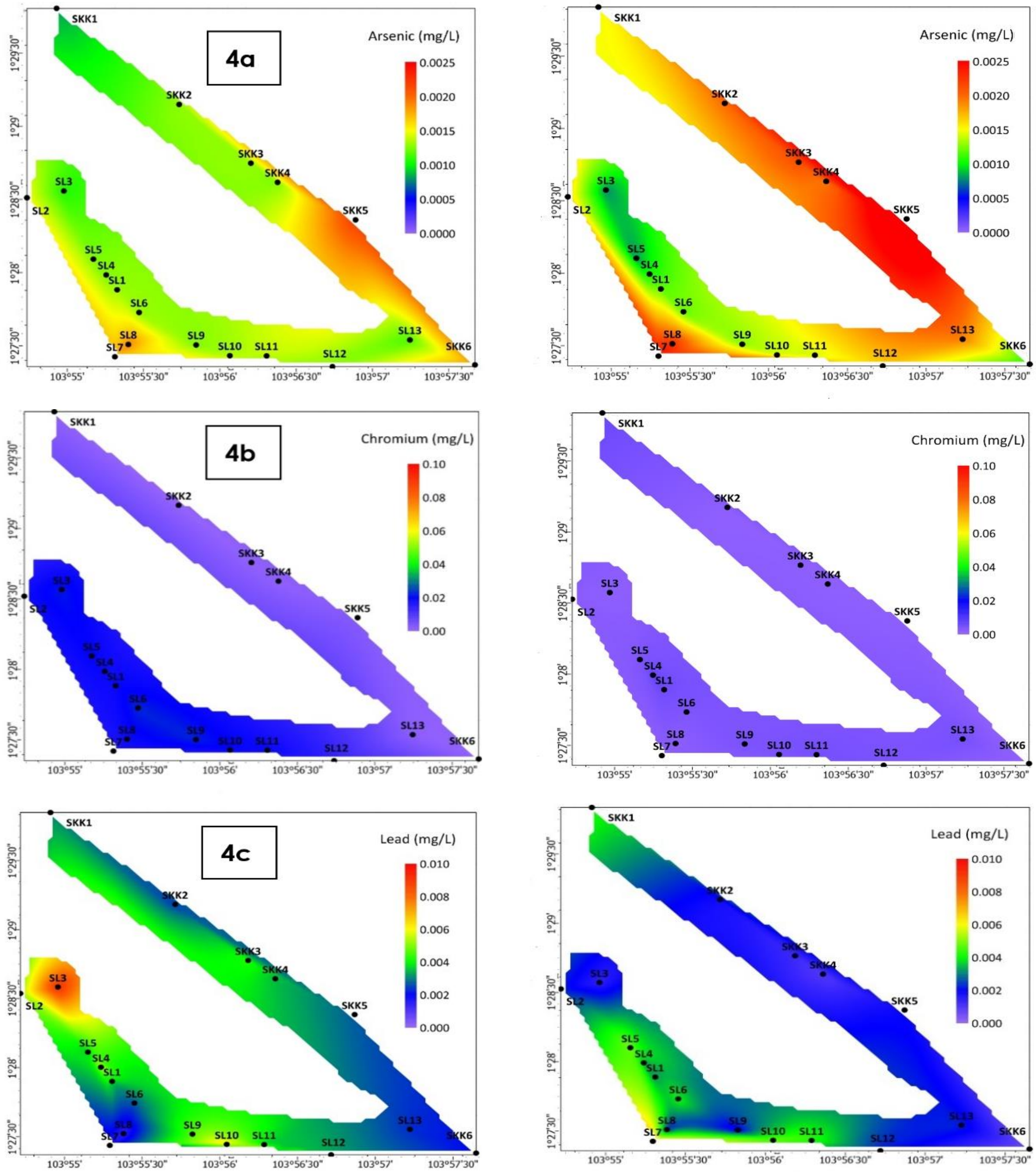
Figure 3. The distribution pattern of heavy metals at Selangkah River.

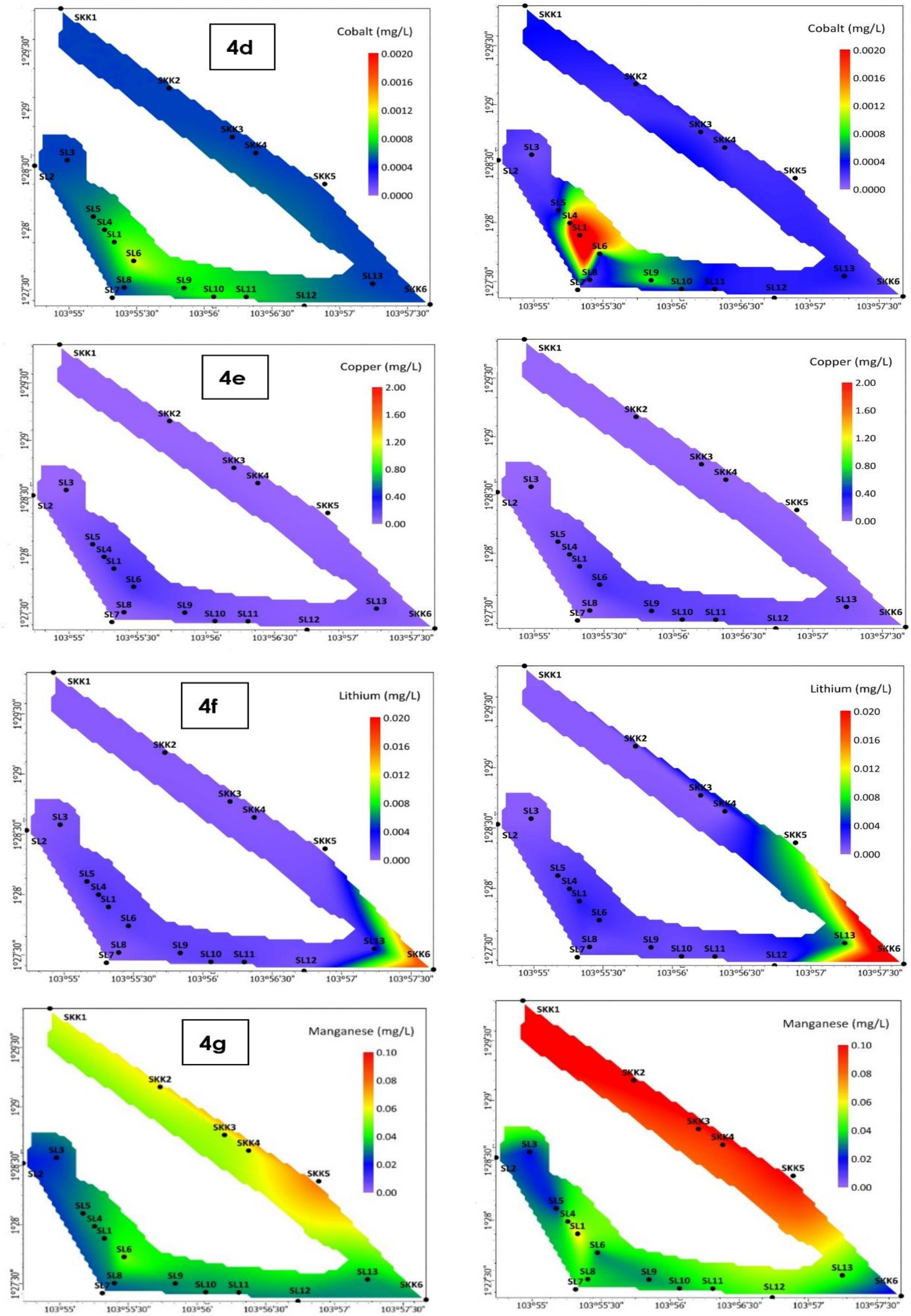
3.4. Selangkah and Kim Kim Rivers heavy metals distribution pattern (December 2020 and January 2021)

According to the assertions from December 2020, Selangkah River had tremendous concentrations of heavy metals at SL7 and SL8. However, the quantity of heavy metals in Kim Kim River was equivalent to Selangkah River at SKK5. The outcome from January 2021 also showed that the sampling stations along the Kim Kim River had comparatively higher levels of heavy metal content. Besides this, in December 2020, the Selangkah River had a significantly larger Cr accumulation than the Kim Kim River at all sampling sites. On the other hand, Cr levels decreased in all the sampling locations along both rivers in January 2021. The SL1 and SL6 sampling sites did not show any appreciable variations in Cr quantities from December 2020 sampling activity. Pb and Co concentrations were elevated in the Selangkah River, particularly at the SL3 (for Pb) and SL6 (for Co) sampling sites. The Co content, on the other side, was highest at the SL1 and SL6 sampling sites in January 2021, despite the reality that Pb concentrations were low in all sampling locations (Figure 4a–4l).

Notably, the Cu content was consistent (0.2 mg/L) throughout all sampling locations for both rivers, whereas the highest Li concentration was at the SKK6 sampling location, where the two rivers joined to form a singular water source. All sampling stations in the Kim Kim River had comparatively high Mn concentrations, but the SKK5 location had the highest concentrations when compared to the Selangkah River sampling station. The outcomes of the January 2021 results were quite obvious. At sampling sites along the Selangkah River, particularly at SL5, SL7, and SL8, where the results were consistent with earlier discoveries, it was discovered that Fe concentrations were quite elevated. Results from the same sampling location in January 2021 still indicated greater Fe amounts. When compared to all other sampling sites along the Selangkah River and the Kim Kim River, the predominant amounts of K and Mg elements were found at the SKK6 sampling station. However, their limit was within the range permitted for open water. The concentrations of the Ni and Zn components did not go above the highest permitted level either. Moreover, SL1, SL4, SL5, and SL6 sampling stations in the Selangkah River had a comparatively greater amount of heavy metals than the Kim Kim River sampling stations (SL11 sampling stations were added). In addition, it was determined that sampling in January 2021 led to greater Zn concentrations at all sampling locations in the two waterways (Figure 4a–4l).

Overall, it was discovered that sampling stations SL1, SL4, SL5, and SL6 demonstrated the presence of heavy metals in greater amount when compared to other Selangkah River sampling stations. Apart from As and Mn in the SKK5 sampling location, the Kim Kim River sampling sites did not demonstrate a substantial variation for most heavy metals present in high concentrations. The findings regarding the heavy metal distribution pattern showed a consistent pattern in both the heavy metal's first and second distribution patterns. The results revealed that Li, K, and Mg, heavy metals, were spread quite far to the southeast to the location where these two waterways emerged. At the SL7 and SL8 sample sites, As and Fe were dispersed and had comparatively higher accumulations. Moreover, it was discovered that the spread of As, Mn, Fe, and Zn in the water of the Kim Kim River showed an increased tendency (Figure 4a–4l).




4d
Cobalt (mg/L)
0.0020
0.0016
0.0012
0.0008
0.0004
0.0000
4e
Copper (mg/L)
2.00
1.60
1.20
0.80
0.40
0.00
4f
Lithium (mg/L)
0.020
0.016
0.012
0.008
0.004
0.000
4g
Manganese (mg/L)
0.10
0.08
0.06
0.04
0.02
0.00
SKK1
SKK2
SKK3
SKK4
SKK5
SKK6
SL1
SL2
SL3
SL4
SL5
SL6
SL7
SL8
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SL12
SL13
103°55'
103°55'30"
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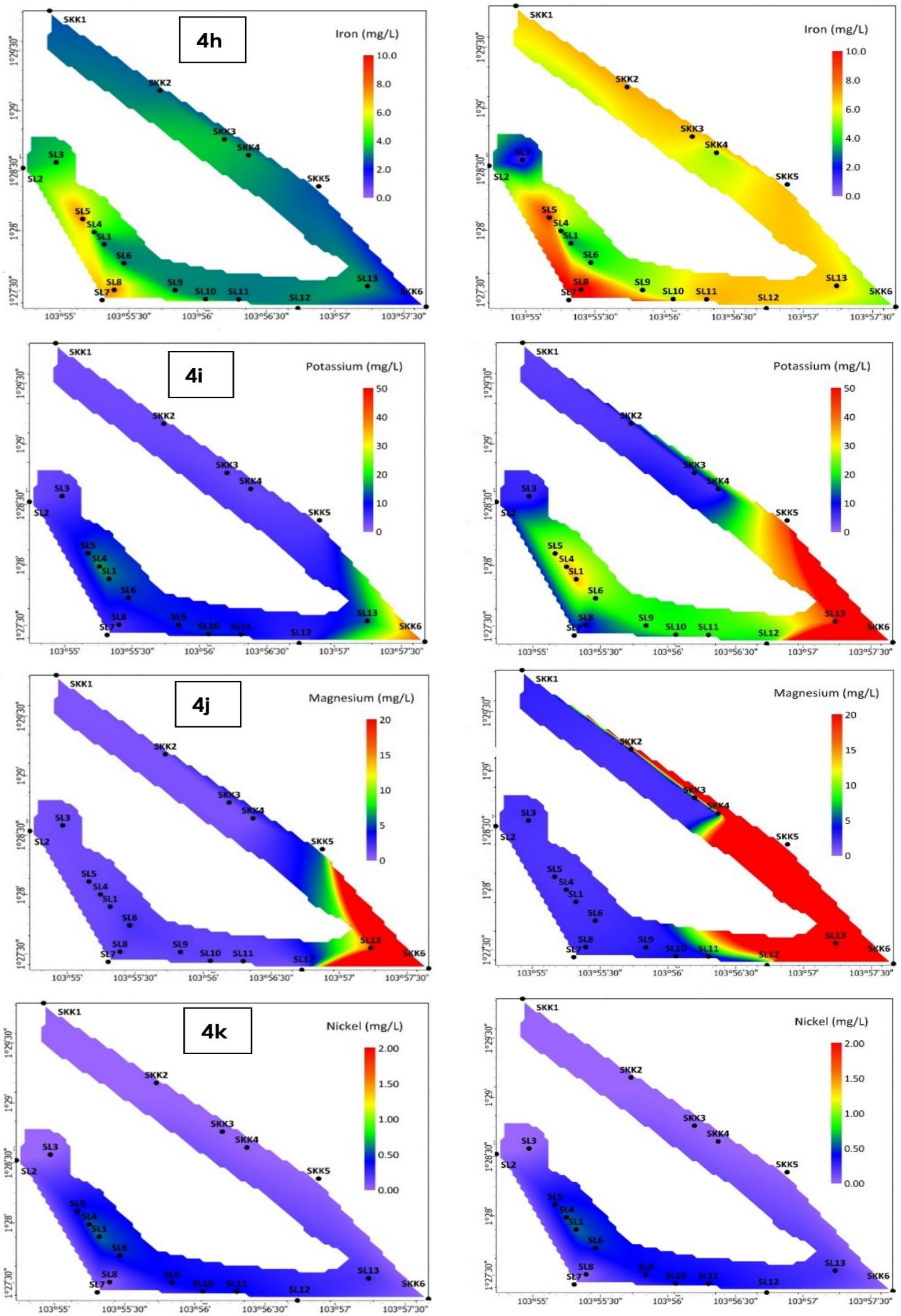
4h
Iron (mg/L)
10.0
8.0
6.0
4.0
2.0
0.0
4i
Potassium (mg/L)
50
40
30
20
10
0
4j
Magnesium (mg/L)
20
15
10
5
0
4k
Nickel (mg/L)
2.00
1.50
1.00
0.50
0.00
SKK1
SKK2
SKK3
SKK4
SKK5
SKK6
SL1
SL2
SL3
SL4
SL5
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SL7
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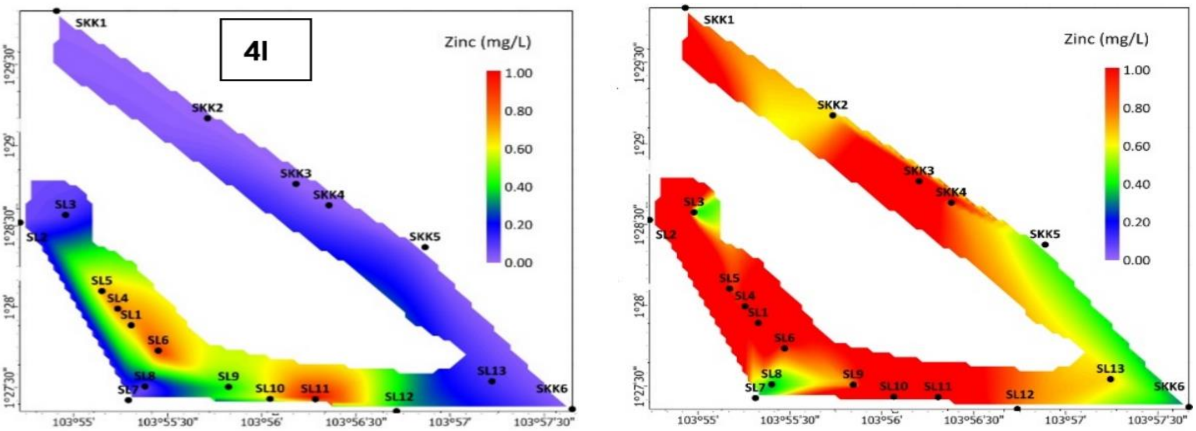

Figure 4. Distribution pattern of twelve heavy metals along the Selangkah and Kim Kim Rivers, illustrated using Natural Neighbor method in Surfer 12.

The presence of heavy metals in a river system can be instigated from natural or anthropogenic sources, and their spatial distribution can be influenced by adsorption, hydrolysis, and co-precipitation [27,28]. As shown in Figures 3a–3l and 4a–4l, the spatial distributions of the heavy metals were not uniform. The highest average concentrations of Fe (9.45mg/L), Cu (0.75mg/L), and Ni (1.04mg/L) in Selangkah river water, recorded at sites SL1, SL4, SL5 and SL6, reflect to higher ions dissolved in the water or may be due to addition of effluent discharges. Moreover, sites 7 and 8 showed highest Fe concentration (> 9 mg/L) which we assumed could be due to higher metal and metal plating industry based activities.

This study also indicates that the average concentration of As, Cr, Pb, and Zn in water samples from both rivers are below the permissible limits recommended by the NWQS and the MOH. However, for Cu, only one station SL6 in the Selangkah River showed an average Cu concentration (0.315 mg/L) slightly above the NWQS allowable limit of 0.02 mg/L for raw water. Cr is a vital micronutrient for animals and plants, and the concentration in surface water is very low [29]. However, water contamination with Cr is caused by intensive industrial activities, e.g., metallurgical processing, electroplating, leather tanning, pigments, textiles, and chemical processing [30].

As evidenced by water samples taken from sampling stations SL1, SL4, SL5, and SL6 in Sungai Selangkah, this research revealed that, overall, river treatment and rehabilitation efforts have not been able to significantly reduce the prevalence of heavy metal elements in river water, particularly Fe, Cu, and Ni. This scenario is probably a result of the activities of some companies in the research region, which are releasing untreated effluent without restriction. As a consequence, it is also conceivable that surface water will seep into the reservoir and contaminate the groundwater. This situation developed as a result of field data that revealed the sewer and drainage system was harmed and poorly maintained.

There are some approaches that are potentially able to control or reduce heavy metal pollution in river ecosystems. Among are through implementing best management practices (BMPs) to reduce the amount of heavy metals entering rivers. BMPs may include erosion control measures, proper disposal of hazardous waste, and reducing the use of heavy metals in the industrial products. Use of alternative technologies that do not rely on heavy metals also help the industries to reduce the amount of heavy metals released into a river system. In addition, implementing effective water treatment processes also can remove heavy metals from polluted water before it is discharged into rivers. Regulation and enforcement by relevance agencies can regulate industrial discharges and enforce laws related to heavy metal pollution. This may include monitoring and testing, as well as penalties for non-compliance. Promoting a public awareness about the risks of heavy metal pollution and how to prevent it can encourage individuals and organizations to take action to reduce pollution. In general, a combination of these approaches can be used to effectively control or reduce heavy metal pollution in river ecosystems. The specific approach used will depend on the nature and extent of the pollution, as well as local regulations and resources.

3.5. Pollution index assessment

The calculated pollution indices provided a definitive classification of the pollution status of the two river systems.

As shown in Table 3, the Selangkah River recorded an HPI value significantly above the critical pollution index of 100 and a high C_d value, confirming a state of severe heavy metal contamination due to the cumulative effect of elements like Fe, Cu, and Ni. The Kim Kim River, while demonstrating lower pollution relative to the Selangkah River, recorded an HPI close to the critical level and a medium C_d, indicating a definite pollution risk, largely driven by Mg and Fe concentrations.

Table 3. Summary of heavy metal pollution index (HPI) and contamination index (Cd) for Selangkah and Kim Kim Rivers.

River	Heavy Metal Pollution Index (HPI}	Pollution status classification	Contamination index (C_d)	C_d Classification
Selangkah River	185.0	Highly Polluted (> 100)	4.5	High (3–6)
Kim Kim River	95.0	Medium-High Pollution	2.8	Medium (1–3)

4. Discussion

The spatial analysis and pollution index assessment confirm that the Selangkah and Kim Kim Rivers in Pasir Gudang are experiencing significant water quality degradation driven mostly by industrial and urban activities. The discussion is structured to interpret the concentrations of major cations and toxic heavy metals in the context of the calculated pollution indices and local regulations.

4.1. Physico-chemical context

The low mean DO values recorded, particularly in the Kim Kim River (1.51 mg/L), suggest poor health in terms of organic pollution. Low DO can significantly affect aquatic life and influence the redox potential of the water, thereby increasing the solubility and mobility of certain metals, such as Fe and Mn. The high mean EC (5408.25 ± 11533.30) and Salinity (3.18 ± 6.93) observed in the Kim Kim River, combined with the very large standard deviation, suggests significant influence from tidal saltwater intrusion or highly concentrated, intermittent effluent discharges containing dissolved salts. This contrasts with the lower mean EC in the Selangkah River (2383.13 ± 5703.80).

4.2. Major cations and geogenic/urban influence

K and Mg are the dominant cations. The Kim Kim River exhibited a notably higher average K concentration (34.07 mg/L) than the Selangkah River (15.62 mg/L). This high concentration is likely associated with increased urban runoff, the leaching of K from surrounding soils, or wastewater discharges [31].

Mg was confirmed as a major cation in the Kim Kim River, with the highest concentration recorded at SKK6 (412.63 mg/L), which is a maximum recorded value, not the river's average. However, the river's mean Mg concentration (81.42 ± 150.20 mg/L exceeds the MNWQS permissible limit of 150 mg/L [32]. While Mg presence is often influenced by natural weathering, the magnitude of this exceedance, particularly the peak concentration, strongly indicates a point-source discharge from an industrial or urban source, likely in the immediate vicinity of SKK6.

Fe concentrations in both rivers exceeded the MOH limit of 1.0 mg/L. The overall average Fe concentration in the Selangkah River (4.591 mg/L) and Kim Kim River (4.463 mg/L) were comparable and significantly high. The highly industrialized nature of the Selangkah catchment, with metal processing and plating activities, is the most probable source for this severe Fe contamination [33].

4.3. Toxic metal exceedances and pollution risk

The most significant pollution risk comes from Cu and Ni in the Selangkah River, which drove the HPI to a highly polluted status. The mean concentrations of Cu (0.157 mg/L) and Ni (0.493 mg/L) significantly exceeded their respective MNWQS limits (0.02 and 0.9 mg/L). These exceedances are concentrated at sites SL1, SL4, SL5, and SL6, which are directly adjacent to heavy industrial zones. Cu is often linked to pipe corrosion and electroplating, and Ni to alloy production and industrial effluent [34].

Although concentrations of other metals like As, Cr, Pb, and Zn remained below the immediate critical thresholds, their presence contributes cumulatively to the overall pollution burden, as demonstrated by the high Cd value for the Selangkah River (4.5). Chronic exposure to these mixed contaminants poses known health risks, including potential organ damage and increased cancer risk [35].

4.4. Pollution index interpretation

The calculated HPI for the Selangkah River (185.0) places it unequivocally in the highly polluted category. This finding moves the assessment beyond simple comparison to water quality standards by providing a definitive, cumulative measure of the health risk posed by multiple heavy metals. The Cd classification of High (4.5) further confirms the severe local contamination in the Selangkah catchment. While the Kim Kim River's pollution indices are lower, the classification of Medium-High pollution status indicates that continuous and unchecked discharges risk tipping this river into the highly polluted category as well.

5. Conclusions

We successfully assessed the heavy metal pollution status of the Selangkah and Kim Kim Rivers in the Pasir Gudang industrial catchment. The findings provide critical baseline information on heavy metal prevalence, concentration, and spatial distribution patterns.

The key conclusions are:

1. Severe Pollution Status: The Selangkah River is confirmed to be highly polluted, with a HPI significantly exceeding the critical threshold of 100 and a Cd categorized as High.
2. Specific Contaminants: The major drivers of this pollution are Fe, Cu, and Ni, whose mean concentrations exceed Malaysian National Water Quality Standards (MNWQS) and are concentrated at

industrial discharge points (SL1, SL4, SL5, SL6).

3. Persistence of Risk: Despite historical remediation efforts, heavy metal elements persist due to their lack of natural degradation and continuous pollutant input from surrounding industrial and urban areas.

To control and reduce this pervasive contamination and mitigate detrimental effects on the aquatic ecosystem, the government and relevant agencies are strongly suggested to take active surveillance measures. These measures should include implementing strict effluent monitoring and enforcement, promoting the use of alternative, less metal-intensive technologies by industries, and exploring targeted effective water treatment processes to remove heavy metals before discharge.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Lakam Anak Mejus led the conceptualization of the study, including the development of the research framework and overall direction. He designed the sampling strategy, field protocols, and laboratory workflow. He also contributed to the preparation of the initial full manuscript, including results interpretation and discussion. Rahman Bin Yaccup verified data accuracy and laboratory results. He critically reviewed the manuscript and contributed to technical refinements. Zalina Binti Laili and Azian Binti Hashim conducted the laboratory analyses of water samples, including ICP-MS procedures. They ensured precision, calibration, and adherence to QA/QC protocols. Both organized and integrated laboratory results into the main dataset and provided technical feedback on the methodology and results sections. Mohamad Syahiran Bin Mustaffa and Mohd Muzamil Bin Mohd Hashim assisted with field sampling, in-situ water quality measurements, and sample preservation. They coordinated sampling schedules, equipment preparation, and site accessibility. In addition, they supported statistical analyses, GIS mapping, and visualization, contributing to the spatial interpretation of pollution patterns. Geoffery James Gerusu coordinated project timelines and reporting. He provided scientific guidance, oversight, and refinement of the research direction. He also edited multiple manuscript drafts, strengthening the overall flow and coherence. All authors have read and approved the final version of the manuscript for publication.

Conflict of interest

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors confirm that they have no conflicts of interest to disclose.

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