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Integrated Assessment of Water Quality and Heavy Metal Contamination in Water and Aquatic Biota of the Otomona River, Indonesia

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Abstract

River systems are vulnerable to contaminant transport and accumulation, yet integrated evidence from tropical regions remains limited. This study aims to investigate physicochemical properties and spatial distribution of dissolved heavy metals in Otomona River water and aquatic biota were assessed. Surface water samples were collected from nine sites (AP01–AP09), encompassing the upstream, middle, downstream, and estuarine sections. The investigation measured total suspended solids (TSS), pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total nitrogen (TN), and total phosphorus (TP). River conditions were further evaluated using the Pollution Index (PI) and Water Quality Index (WQI), and MIKE 21 was used to examine the spatial distribution of mercury (Hg), cadmium (Cd), copper (Cu), lead (Pb), and chromium (Cr). Generally, the physicochemical parameters conformed to relevant standards. PI values, ranging from 0.63 to 0.96, indicated compliance with the water quality criteria at all monitoring sites. A WQI score of 70 classified the river as having good water quality. Most dissolved metal concentrations in the river water were considered safe according to Indonesia's standard except for Cu, which exceeded the Class II limit of 0.02 mg/L at AP08 and AP09. Additionally, in fish tissues, Hg (< 0.005 mg/kg) and Cd (0.0514–0.0759 mg/kg) complied with the applicable Indonesia standards, whereas Pb (0.002–1.0757 mg/kg) exceeded the permissible limit at certain samples. The model demonstrated an increase in metal concentration towards the lower river and estuary, although the spatial patterns varied among metals. Future research should incorporate seasonal monitoring and include microbiological indicators, metal speciation, sediment, aquatic life, and hydrological factors to provide a more comprehensive evaluation of the river's long-term ecological status.

1. INTRODUCTION

Freshwater ecosystems are fundamental to both ecological integrity and human well-being, as they provide water, support fisheries, regulate nutrient cycles, and sustain biodiversity [1, 2]. Despite their significance, these ecosystems are rapidly deteriorating due to the combined pressures of industrialization, urban expansion, and agricultural growth. Currently, about one-third of global freshwater discharge is processed through human-made infrastructure, which introduces contaminants [1, 3].

River degradation typically arises from the interaction of multiple pressures rather than a single pollution source. A systematic review of 88 studies conducted across 34 countries attributed about 60% of the reported pollution effects to urban and industrial land use [4]. Major contributors to declining river health include untreated sewage, industrial effluents, and agricultural runoff [5]. Organic pollution loads may increase significantly with population growth and economic development. These challenges are further exacerbated by climate change, river fragmentation, dam construction, nutrient enrichment, and the introduction of non-native species. The cumulative effects of these factors extend beyond physicochemical deterioration to include habitat modification, biodiversity loss, and reduced ecosystem

services [2, 6, 7]. As a result, the protection of freshwater ecosystems needs coordinated monitoring, effective regulation, and management strategies that consider multiple interacting stressors.

Among the contaminants in the river system, heavy metals are of particular concern due to their persistence, non-biodegradability, and ability to accumulate in sediments and biological tissues [8, 9]. Once released, these metals can be transported in dissolved or particulate forms, deposited in riverbed sediments, and subsequently remobilized when hydrological or physicochemical conditions change. This persistence feature leads to ecological risks to aquatic organisms and potential health risks to communities dependent on rivers as their water and food sources. Exposure may occur directly through water use or indirectly through the consumption of contaminated fish and crops irrigated with polluted water, as well as through the redistribution of contaminated sediments during floods [10].

River monitoring often relies only on physicochemical variables such as temperature, pH, DO, BOD, COD, nutrients, and suspended solids. Although these parameters provide essential information, interpreting numerous variables simultaneously can be challenging, particularly when comparisons are required across different monitoring locations. Water quality indices address this limitation by combining selected parameters into a single metric that represents overall water conditions. Previous applications have demonstrated the use of WQI in identifying pollution-prone locations and supporting water resource management [11–13]. In this study, the PI was applied as an integrative water quality assessment approach. However, an index may obscure individual contaminant behavior and generally represents conditions only during the sampling period; therefore, it should be interpreted alongside parameter-specific measurements and biological evidence.

Meanwhile, aquatic organisms provide complementary information because they integrate contaminant exposure over longer periods than individual water samples do. Fish and other aquatic biota continuously absorb metals through their gills, body surfaces, and diet, after which the contaminants may accumulate in the liver, kidneys, gills, and muscle tissues. Accumulation patterns vary according to metal properties, species, habitat, trophic position, and physiological regulation. Hg is particularly associated with dietary transfer and biomagnification, whereas Cd and Pb commonly accumulate in benthic organisms and metabolically active tissues of fish. Cr may undergo bio dilution or remain concentrated in particular organs, whereas Cu exhibits more variable behavior because it is an essential element subject to physiological regulation [14–21]. Therefore, metal concentrations in aquatic biota can indicate cumulative exposure and ecological risk that may not be apparent from water measurements alone.

River-estuarine systems affected by mining activities are particularly vulnerable to this heavy metal contamination because they act as natural sinks for suspended sediments and associated pollutants transported from upstream catchments. The transport, deposition, resuspension, and redistribution of contaminants within these environments are controlled by complex hydrodynamic processes, including river discharge, tidal forcing, and sediment dynamics. Consequently, field observations alone are often insufficient to fully characterize the spatial distribution and fate of contaminants in these systems.

Hydrodynamic and water quality models have become important tools for understanding pollutant transport mechanisms and predicting environmental responses under varying hydrological conditions [22]. Recent studies [23, 24] have emphasized the value of numerical modelling approaches in supporting river water quality management and evaluating contaminant transport pathways in complex aquatic environments).

The Otomona River in Mimika Regency, Central Papua, Indonesia, is an ecologically important river estuary system that supports fishery resources, aquatic biodiversity, and the livelihoods of local communities. The river receives inputs from upland catchments influenced by mining activities before discharging into the Arafura Sea. This hydrological setting creates conditions conducive to the transport and accumulation of suspended sediments and associated contaminants in downstream aquatic environments. Despite the environmental significance of the Otomona River, scientific information regarding its water quality status, heavy metal contamination in aquatic biota, and pollutant transport dynamics is limited. Existing studies on mining-affected tropical river systems have generally focused on either water quality assessment or contaminant concentrations, whereas integrated investigations combining water quality indices, bioaccumulation assessment, and hydrodynamic modelling remain relatively scarce.

Therefore, this study aimed to evaluate the physicochemical characteristics of the Otomona River, determine its water quality status using the Water Quality Index (WQI) approach, assess heavy metal concentrations in water and aquatic biota as indicators of ecosystem health, and simulate hydrodynamic conditions and pollutant distribution using the MIKE 21 modelling framework. By integrating field observations with numerical modelling, this study provides a comprehensive assessment of water quality in a tropical mining-influenced river system and contributes valuable information for sustainable river basin and estuarine management in the eastern Indonesia.

2. METHODOLOGY

2.1 Data Collection

The sampling process was conducted along the Otomona River in nine segments, predetermined based on the river's physical characteristics and the distribution of activities surrounding it (Fig. 1). In each segment, water samples were collected by considering the distance between points and the river's average flow speed, ensuring that the samples accurately represented the hydrological conditions of that segment. Water sampling was conducted at two transverse points, specifically at 1/3 and 2/3 of the river width, with a retrieval depth of 0.5 times the total water surface depth. This protocol ensured that the collected samples accurately reflected the water quality conditions throughout the stream section. By adhering to this procedure, comprehensive water quality data were obtained to characterize the condition of the Otomona River.

The analysis of water quality and fish samples was conducted by BBSPJIHPMM under the auspices of the Indonesian Ministry of Industry, while hydrological data were obtained through field surveys. The analysis considered water temperature and TSS as physical parameters, alongside chemical parameters such as pH, BOD, COD, DO, total nitrogen (TN), total phosphate (TP), and dissolved metals, including Hg, Cd, Cu, Pb, and Cr.

At each sampling point, river water was initially collected using a plastic bucket as a temporary container. Subsequently, the water was transferred into a 1000 ml jerry can and a 150 ml Winkler bottle for DO analysis. Upon completion of the transfer process, the jerry can contain the sample was placed in a cooling box to maintain the stability of the sample's physical and chemical conditions. Temperature measurements were conducted directly on the water in the bucket using a thermometer before the samples were preserved in a cooling box. Subsequently, the collected samples underwent laboratory testing, and the analysis steps for each parameter adhered to standard methods.

Meanwhile, a total of ten (10) fish specimens were obtained using a random sampling technique to ensure representativeness of the fish population inhabiting the river. Immediately after capture, specimens were placed in labeled sterile polyethylene bags and stored in a cool box (± 4°C) to minimize tissue degradation during transport to the laboratory.

In the laboratory, each fish was rinsed with distilled water to remove surface debris, then dissected to separate the internal organs, gills, and flesh (muscle tissue). These three tissue types were combined into a single composite sample per specimen to represent the overall accumulation of heavy metals within the fish body. The composite samples were homogenized and oven-dried at 60–105°C until a constant weight was reached, then ground into a fine powder in preparation for chemical analysis.

Heavy metal extraction was carried out through wet digestion. Sample was digested using a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) on a hot plate until a clear digest was obtained. The digest was cooled, filtered through Whatman No. 42 filter paper, and diluted with deionized water. The resulting solution was analyzed for heavy metal content (Pb, Cd, Hg, Cu, Cr) using an Atomic Absorption Spectrophotometer (AAS).

2.2 Data Analysis

2.2.1 Water Quality Index

Water quality data for each monitoring period were assessed using the Pollution Index (PI) method. This method was chosen due to its ability to provide a comprehensive evaluation of water pollution by integrating multiple water quality parameters. The PI assessment adhered to the provisions outlined in the Regulation of the Minister of Environment and Forestry No. 27 of 2021 [25]. The assessment included key physical and chemical parameters that represent the overall pollution condition, TSS, pH, BOD, COD, DO, TN, and TP. Water quality was evaluated by comparing the measured concentrations with the Class II water quality standards specified in Appendix VI of Government Regulation No. 22 of 2021

[26], which pertains to the Implementation of Environmental Protection and Management. Class II water is designated for uses such as irrigation, freshwater aquaculture, livestock farming, and other applications requiring a similar level of water quality. The PI value was derived from the ratios between the measured concentrations and their corresponding water quality criteria. This value was subsequently used to determine the water quality status at each monitoring location and period. The PI was calculated using the equation presented in Eq. 1 below.

$$PIJ = \sqrt{\frac{\left(\frac{C_i}{L_{ij}}\right)^2_{Max} \pm \left(\frac{C_i}{L_{ij}}\right)^2_{average}}{2}} \quad (1)$$

In this equation, (Lij) represents the water-quality standard for parameter (i) and designated water use (j), whereas (Ci) represents the measured concentration of parameter (i). The term (PIj) denotes the Pollution Index for designated water use (j).

The water quality status at each monitoring location was determined in accordance with the Decree of the Minister of Environment No. 115 of 2003 [27], which provides the Guidelines for Determining Water Quality Status, and the Regulation of the Minister of Environment and Forestry No. 27 of 2021. The PI classifications were as follows; $0 \leq PI_j \leq 1$ means meets the water quality standards; $1 < PI_j \leq 5$ is lightly polluted; $5 < PI_j \leq 10$ is moderately polluted; and $PI_j > 10$ is categorized as heavily polluted.

2.2.2 Analysis of Heavy Metals in Water and Biota in the Otomona River

The examination of heavy metals in water and aquatic organisms is crucial for evaluating pollution levels and their potential effects on the environment and on human health. To conduct this analysis, the concentrations of metals such as Hg, Pb, Cd, Cu, and Cr in river water were quantified. Water samples collected from the monitoring sites were analyzed in the laboratory using methods aligned with the Indonesian National Standard (SNI) series no: 6989 for water quality [28]. The findings were then compared with the river water quality standards specified in Government Regulation Number 22 of 2021 [26]. In addition to water, heavy metals are assessed in aquatic organisms, such as fish, to determine metal accumulation within these organisms. Heavy metal concentration data obtained from the Atomic Absorption Spectrometry (AAS) measurements were expressed in mg/kg then the value compared against maximum permissible limits established by relevant regulatory standards to assess the potential health risk associated with fish consumption.

2.2.3 MIKE 21 Modeling

This study used a simulation using the MIKE 21 Hydrodynamic (HD) Module to model the hydrodynamic conditions of the Otomona River, specifically the flow velocity and direction. In river systems, tidal influences can be adjusted according to local conditions. If tidal influences are significant downstream, tidal data are used as an open boundary, whereas in flow-dominant river segments, flow velocity and

discharge are the main driving factors. Furthermore, simulations of heavy metal distribution were performed using Ecolab's MIKE 21 Module. Heavy metals such as Hg, Pb, Cd, Cu, and Cr were modeled as water quality parameters by entering the initial concentrations and pollutant sources (source terms) based on field measurements.

3. RESULT AND DISCUSSION

3.1 Water Quality Index

The physicochemical properties of the Otomona River were evaluated at the designated sampling sites. These findings were then compared with the Indonesian Class II water-quality standards, as detailed in Table 2.

Table 2
Pyshiochemical characteristics of Otomona river water quality

Sampling point	Temperature deviation	TSS	pH	BOD	COD	DO	TN	P
	°C	mg/L	-	mg/L	mg/L	mg/L	mg/L	mg/L
AP01	2.9	10	7.4	2.4145	21.0398	6.2	5.3821	0.0202
AP02	2.3	9	7.4	2.6212	18.3331	7.46	3.6247	0.0145
AP03	0.7	8	7.5	1.9631	20.1153	6.02	2.3066	< 0.01
AP04	0.3	8	7.8	2.3212	23.1724	6.02	2.5263	0.0102
AP05	3.7	10	7.8	1.5739	18.7726	6.66	1.9771	0.0115
AP06	3.8	9	8.1	1.7992	12.6251	7.07	1.0984	< 0.01
AP07	5	11	8.2	2.0021	19.3825	6.28	1.6476	0.0236
AP08	3.2	9	7.9	2.1081	19.875	6.41	2.8558	0.0109
AP09	3.3	8	8	1.9766	15.1919	7.06	3.5148	0.0201

As summarized in Table 2, the physicochemical characteristics of the Otomona River generally complied with the Class II water-quality criteria stipulated in Indonesian Government Regulation No. 22 of 2021. Water temperatures ranged from 28.7 to 31.7°C, whereas ambient air temperatures during sampling ranged from 30 to 35°C, resulting in water–air temperature differences of 0.3–5.0°C. These values represent warm tropical river conditions rather than cold waters. Because the applicable criterion permits a maximum deviation of 3°C from the ambient air temperature above the water surface, several monitoring locations may have exceeded the temperature criterion. These differences may be associated with variations in sampling time, solar exposure, riparian shading, water depth, and flow. of 50 mg/L. This indicates a relatively low suspended particle load and limited sediment-related

disturbance during the monitoring period. However, TSS may vary considerably in response to rainfall, erosion, and discharge; therefore, the measured range may not represent wet season or high flow conditions. The recorded pH values of 7.4–8.2 were also within the permitted range of 6–9, indicating neutral to mildly alkaline conditions that are generally suitable for aquatic organisms and for normal biogeochemical processes.

The organic pollution indicators showed greater spatial concern, despite remaining within the applicable standards. BOD concentrations ranged from 1.5739 to 2.6212 mg/L, which is below the Class II limit of 3 mg/L. However, the highest concentration reached approximately 87% of the threshold, indicating a relatively elevated biodegradable organic load at specific locations. Similarly, COD concentrations ranged from 12.6251 to 23.1724 mg/L, with the maximum value reaching approximately 93% of the 25 mg/L limit value. The near-threshold BOD and COD concentrations at some stations may indicate localized inputs of organic or other oxidizable materials. Potential sources may include domestic wastewater, surface runoff, decomposing natural organic matter, or other activities within the catchment, although source attribution requires supporting land use and discharge data. However, DO concentrations showed value between 6.02 and 7.46 mg/L, which is substantially above the minimum Class II requirement of 4 mg/L. The combination of relatively low BOD and high DO suggests that the river maintained adequate assimilative and reaeration capacities during sampling. Nevertheless, because DO varies diurnally and is influenced by temperature, flow turbulence, photosynthesis, and respiration, continuous or early morning measurements would provide a more conservative assessment of oxygen availability.

Nutrient concentrations also remained below the Indonesia regulatory thresholds. TN ranged from 1.0984 to 5.3821 mg/L, corresponding to approximately 7–36% of the Class II limit (15 mg/L). The total phosphate as P ranged from below 0.01 to 0.0236 mg/L, with the maximum concentration representing approximately 12% of the 0.2 mg/L limit. These results indicate no substantial nitrogen or phosphorus enrichment during the sampling period. Nevertheless, both nutrients remain ecologically important because excessive input can stimulate algal growth and contribute to eutrophication. TN and total phosphate concentrations may also vary seasonally in response to agricultural runoff, domestic discharge, sediment transport, and changes in river flow.

Overall, the TSS, pH, BOD, COD, DO, TN, and total phosphate results indicated generally favorable physicochemical conditions in the Otomona River during the monitoring period. However, the temperature deviations recorded at several stations and the near-threshold BOD and COD concentrations indicate potential localized pressures that should not be overlooked in the future. Consequently, the present findings should be interpreted as a representation of the conditions during the sampling period rather than as definitive evidence of consistently good water quality. Monitoring during both wet and dry seasons, supported by discharge, land use, and pollution-source data, is recommended to determine whether the observed spatial patterns are temporary or persistent.

The pollution status of the Otomona River was assessed using the Pollution Index (PI), which combines various parameters that indicate different pathways of water quality degradation. TSS signifies

particulate matter, pH reflects acid–base balance, BOD and COD denote biodegradable and chemically oxidizable substances, DO indicates oxygen levels, and TN and TP represent nutrient enrichment. By integrating these parameters into a single index, the interpretation of complex monitoring data is simplified, and a practical means for comparing water quality across different sampling sites is offered [29, 30].

The PI values calculated at all monitoring stations were within the acceptable range (PI ≤ 1) as seen in Fig. 2, indicating that the Otomona River met the relevant water quality standards or was unpolluted. This suggests that the combined effects of suspended solids, organic matter, oxygen levels, and nutrient concentrations did not exert a significant pollution pressure during the sampling period. Based on the proportion of monitoring sites within each PI category, the Otomona River received a Water Quality Index (WQI) score of 70. According to the classification from Indonesian Ministerial Regulation No. 27 of 2021, this score falls within the “good” category (70 ≤ WQI < 90), although it is at the lower end of that range, which is acceptable. The consistency between the station-level PI results and the overall WQI suggests that the favorable water quality conditions were spatially uniform across the monitored river segment.

However, a WQI of 70 should not be considered as evidence of pristine conditions or the absence of all forms of contamination. Index results depend on the chosen parameters, regulatory thresholds, weighting system, and aggregation method; therefore, different index methods may assign different classifications to the same river [30, 31]. Additionally, a composite index might overlook localized or parameter-specific issues that are not included in its calculation [32]. The current classification should be regarded as indicative of the evaluated parameters and sampling period. Future research should expand the temporal and analytical scope of this study by implementing seasonal monitoring and including microbiological indicators, metals, and hydrological variables in the analysis. Such an expanded approach would offer a more comprehensive understanding of the spatiotemporal variations and long-term ecological status of the Otomona River.

3.2 Heavy Metal Concentration in Otomona River Waters

Heavy metals are classified as hazardous and toxic substances when present in high concentrations in water. Although heavy metals occur naturally in the environment, they are typically found in very low concentrations. Their presence in nature is attributed to processes such as tectonic activity, volcanism, upwelling, and atmospheric deposition. Elevated heavy metal concentrations in water are usually caused by inputs from land-based sources. The concentrations of Hg, Cd, Cu, Pb and Cr measured in the Otomona River are summarised in Fig. 3.

Based on Fig. 3, the distribution of dissolved metals in the Otomona River was characterized by generally low Hg, Cd, Pb, and Cr concentrations, but a distinct increase in Cu at the downstream stations was observed. Mercury was detected below 0.0003 mg/L, below the Class II criterion of 0.002 mg/L, while Cd and Pb concentrations of 0.0007–0.0019 mg/L and 0.0021–0.0059 mg/L remained below their respective limits of 0.01 and 0.03 mg/L. Chromium concentrations ranged from 0.0004 to 0.0097 mg/L. In contrast, Cu ranged from 0.01 to 0.0261 mg/L and exceeded the Class II limit of 0.02 mg/L at AP08

and AP09. This contrast suggests that the observed Cu enrichment was spatially confined rather than indicative of widespread metal contamination throughout the river.

The location of AP08 and AP09 in the lower river and estuarine zone provides several possible explanations for this pattern. Contaminants transported from upstream may accumulate downstream, while reduced flow velocity, tidal mixing, and sediment resuspension near the river mouth may alter the partitioning of Cu between dissolved and particulate phases. Local inputs from mineral weathering, mining-related runoff, industrial activities, domestic discharges, agricultural materials, or corrosion of metal infrastructure may also contribute. The current dataset, however, does not allow a particular source to be identified. The Cu increase should therefore be regarded as evidence of a localized signal requiring source investigation rather than direct proof of a specific anthropogenic activity.

The river's physicochemical conditions may partly explain why most metals remained at low dissolved concentrations. The pH range of 7.4–8.2 indicates neutral-to-alkaline conditions, which generally favor the adsorption of cationic metals onto mineral surfaces and the formation of less soluble hydroxide or carbonate species. The high DO concentrations of 6.02–7.42 mg/L further indicate predominantly toxic conditions. Together, these conditions may restrict the mobility of Cd and Pb, although their effects vary according to metal speciation and sediment composition. Cr requires particular attention because Cr(III) and Cr(VI) behave differently; Cr(III) is generally less mobile under alkaline conditions, whereas Cr(VI) may remain comparatively soluble under oxic conditions. Consequently, a low total Cr concentration cannot be used to reliably assess risk without information on the oxidation state.

Low TSS concentrations of 8–11 mg/L may reflect limited erosion and particulate transport, but it also reduces the surface area available for metal adsorption in the water column. This could increase the relative contribution of dissolved metals, particularly in areas where a local source is present. Conversely, high TSS does not necessarily reduce overall metal contamination because particle-bound metals can settle and accumulate in sediment and be released when pH, salinity, or redox conditions change. Therefore, measurements of dissolved metals alone may underestimate the total metal burden retained within the river system.

The influence of organic matter also requires careful interpretation of the results. Although BOD and COD remained below the Class II criteria, these parameters measure oxygen demand rather than the concentration and binding capacity of the dissolved organic matter. Cu forms strong complexes with naturally occurring organic ligands, and this complexation can maintain Cu in the dissolved fraction while reducing the proportion present as bioavailable free ions. Studies have shown that dissolved organic ligands can strongly control Cu speciation and toxicity in natural water [33]. Thus, an elevated dissolved Cu concentration does not necessarily correspond directly to the most toxic fraction of Cu. Measurements of dissolved organic carbon and labile or free Cu are required to evaluate its actual bioavailability.

The relatively low nitrogen and phosphate concentrations are unlikely to be the primary cause of Cu exceedances, although they may indirectly influence metal behavior. Low phosphate availability may limit

the formation of sparingly soluble metal-phosphate phases, whereas nutrient concentrations may affect biological uptake and microbial processes. Nevertheless, metal mobility in aquatic systems is controlled by the combined effects of pH, oxygen, salinity, organic matter, and sediment characteristics, rather than by any single water quality parameter [34]. This interaction is particularly relevant near AP09, where freshwater–estuarine mixing may modify the ionic strength and metal partitioning.

3.3. Heavy Metal Distribution Patterns

Heavy metal concentration distribution in the Otomona River is illustrated in Fig. 4.

The MIKE 21 results generally showed increasing metal concentrations from the upstream to the lower Otomona River, although the patterns differed among elements. The distribution of Hg on the map shows a relatively uniform distribution from the upstream to the downstream parts of the river. Hg concentrations around the sampling locations did not show significant differences although Hg increased from 0.000204 to 0.000234 mg/L in AP01–AP04 to 0.000234 to 0.000276mg/L in AP05–AP08 and reached 0.000270–0.000276 mg/L near AP09.

Meanwhile, the simulation results of Cd concentrations in segments AP01–AP04 are predominantly characterized by purple hues, with values ranging from 0.00072 to 0.00080 mg/L. Cd concentrations increase in segments AP05–AP06, which exhibit predominantly purple–blue hues, with estimated values ranging from 0.00072 to 0.00096 mg/L, and a small area colored green with values ranging from 0.00120 to 0.00136 mg/L. In segments AP07–AP08, the distribution map is primarily green, with values ranging from 0.00128 to 0.00152 mg/L. In the final sampling area, AP09, the distribution map is dominated by shades of green, yellow, and orange, with estimated values ranging from 0.00144 to 0.00176 mg/L. The emergence of green areas in AP05–AP06 signifies the onset of a trend towards Cd accumulation. This trend is typically influenced by a reduction in current velocity, interaction with fine sediments, and potential contributions from activities along the riverbanks. Cd concentrations progressively increase downstream from the middle to the lower reaches, peaking at the estuary, which is identified as the zone of greatest accumulation and classified as an area of higher ecological risk. In this region, there is potential for long-term accumulation and biomagnification if the input of contaminants continues unabated.

Cu exhibited the greatest spatial variability and was the primary metal of concern in this study. The highest measured concentration occurred at AP08 (0.0261 mg/L), followed by AP09 (0.0227 mg/L) and AP07 (0.0188 mg/L), whereas the values at AP03–AP05 were below the detection limit (< 0.010 mg/L). Modeled concentrations increased from 0.000222–0.000240 mg/L in AP01–AP04 to 0.0043–0.020 mg/L in AP05–AP06 and 0.018–0.022 mg/L in AP07–AP08, with part of the downstream area exceeding the 0.02 mg/L standard. Although the measured maximum occurred at AP08, interpolation extended the high-concentration zone toward AP09, suggesting localized Cu inputs, combined with downstream transport and estuarine retention.

Pb remained below the 0.03 mg/L criterion but showed gradual downstream enrichment. Concentrations increased from 0.0021 mg/L at AP01 to 0.0059 mg/L at AP08, while modeled values rose from 0.0027–0.0043 mg/L in AP01–AP06 to 0.0045–0.0047 mg/L at AP07–AP08 and 0.0047–0.0050 mg/L close to AP09. Cr did not exhibit a consistent downstream trend. The highest measured concentration occurred at AP08 (0.0097 mg/L), while the modeled values ranged from < 0.0012–0.0030 mg/L upstream, reached localized concentrations of 0.0048–0.0060 mg/L around AP05–AP08, and declined to 0.0012–0.0024 mg/L at AP09. These concentrations remained below the 0.05 mg/L criterion.

Overall, the lower river and estuary acted as accumulation zones for Hg, Cd, Cu, and Pb, likely due to cumulative transport, slower currents, tidal mixing, and sediment interaction. Most concentrations complied with the applicable standards, but Cu exceedances and modeled Cd enrichment indicate emerging localized pressure. Therefore, AP07–AP09 should be prioritized for source identification and seasonal monitoring of water, sediment, and aquatic biota.

Numerous studies have documented the accumulation of metals in estuarine environments. Niu et al. [35] observed that tidal currents in the Pearl River Estuary facilitate mixing from the surface to the bottom, influencing the distribution of metals. Feng et al. [36] demonstrated that the lower Hudson River estuary contributes metal contaminants to upstream areas through sediment resuspension and lateral advection. Ronco et al. [37] identified coastal plain areas as regional sinks for metals between upstream regions and estuaries. However, the spatial distribution of metals is contingent upon the type of metal and location. Liu et al. [38] found that significant diffusion of heavy metals into the ocean substantially reduced their concentrations in the sediments of the Yangtze River estuary, where Wright and Mason [39] reported that metal concentrations were highest at both the head and mouth of the estuary, rather than exclusively in the lower zone. While mechanisms such as tidal mixing and sediment interaction are supported, cumulative transport and slower currents coexist with other processes like offshore diffusion.

3.4 Heavy Metal Concentration in aquatic biota

The concentration of heavy metals in aquatic organisms is influenced by environmental conditions, trophic levels, species, and age. Exceeding the quality standards for food consumption may pose health risks. The primary sources of heavy metal pollution include industrial activities, mining, agricultural practices (such as fertilizer and pesticide use), household waste, and atmospheric deposition, which contaminate aquatic environments. Table 3 presents the concentrations of heavy metals in the biota of the Otomona River. Laboratory test results, indicate that the majority of heavy metal concentrations in the fish, used as test parameters, comply with the quality standard limits established by the Indonesian National Standard No. 7387 of 2009 [40], which pertains to the Maximum Limits for Heavy Metal Contamination in Food for fish and its processed products.

Table 3
Heavy metal concentration on fish result

Sample No.	Heavy Metal concentration (mg/kg)				
	Hg	Cd	Cu	Pb	Cr
1	< 0.005	0.0531	0.2755	< 0.002	< 0.50
2	< 0.005	0.0536	0.2556	0.0067	< 0.50
3	< 0.005	0.0514	0.1851	0.0069	< 0.50
4	< 0.005	0.0759	0.9260	0.1591	< 0.50
5	< 0.005	0.0618	0.2151	0.2723	< 0.50
6	< 0.005	0.0623	0.5924	0.6358	< 0.50
7	< 0.005	0.0723	0.1813	0.4141	< 0.50
8	< 0.005	0.0681	0.4607	0.8477	< 0.50
9	< 0.005	0.0674	0.3698	1.0757	< 0.50
10	< 0.005	0.0568	0.0246	0.0416	< 0.50
Threshold	0.5–1.0	0.1–1.0	-	0.3–0.4	-

According to the data, the concentration of Pb in the fish varied from less than 0.02 to 1.0757 mg/kg. Notably, several samples exhibited higher Pb levels compared to others. This suggests that Pb accumulates in biota despite its relatively low concentration in the surrounding waters. These findings are corroborated by previous research, which demonstrated that in coastal waters, Pb concentrations in mussels were 50 to 190 times higher than those in the surrounding water [41] and the study of the Emet Stream documented a pattern of Pb accumulation, with sediment showing the highest levels, followed by fish tissues, and then water. Notably, fish tissues exhibited significant accumulation despite the lower concentrations in water [42].

As presented in the Table 3, Hg concentrations in all fish samples were below the detection limit of 0.005 mg/kg, and Cr concentrations were below 0.50 mg/kg. This suggests that the accumulation of Hg and Cr in the test fish was relatively low. The analysis revealed Cd concentrations in fish ranged from 0.0514 to 0.0759 mg/kg, indicating consistent accumulation in fish tissue despite low Cd concentrations in the surrounding waters. This observation aligns with the known propensity of Cd to bioaccumulate in organisms.

Previous studies indicate significant geographical variation in Cd concentrations in riverine fish, with reported values spanning over three orders of magnitude, ranging from 0.001 to 3.48 mg kg^{-1}. In the ten studies reviewed, concentrations in Asia varied from 0.0064–0.0260 ppm in the Keuretoe River, Indonesia [43], to 0.115 mg kg^{-1} in the Yangtze River, China [44] and 0.2–3.48 mg kg^{-1} in the Ganga River

[45] European rivers also exhibited considerable variation, with concentrations reported between 0.001–0.254 mg kg^{-1} in the Czech Republic [46]. Several of these values surpassed the 0.05 mg kg^{-1} maximum level set by the European Commission and the safety thresholds cited by the WHO [47, 48]. However, cross-study comparisons should be approached with caution, as metal concentrations are affected by factors such as fish species, feeding guild, tissue type, body size, and whether results are expressed on a wet- or dry-weight basis. For instance, omnivorous and bottom-feeding fish often accumulate higher Cd levels due to their proximity to contaminated sediments and benthic food sources [49].

Fish absorb Cd through waterborne uptake across the gills and by ingesting contaminated food and sediment, with dietary exposure often significantly contributing to trophic transfer [50–53]. Once absorbed, Cd, Pb, and Cr tend to accumulate in metabolically active organs [54]. In contrast, Hg behaves differently due to its accumulation being strongly influenced by dietary exposure and trophic position, leading to greater retention in muscle and a higher potential for biomagnification [55]. Cu is also distinct as it is an essential element with uptake and internal distribution that are physiologically regulated. Consequently, Cu is commonly retained in the liver and gills and does not typically exhibit biomagnification to the same extent as Hg [56, 57].

In this study, Cu concentrations in fish exhibited a broad range from 0.0246 to 0.9260 mg kg^{-1}. The elevated levels observed in several samples suggest spatial variations in exposure through water, sediment, or diet. While Cu is essential for normal physiological functions, excessive accumulation can overwhelm regulatory mechanisms, leading to toxic effects.

Within the regulatory framework of this study, Hg and Cd concentrations in biota complied with the relevant Indonesian criteria. However, the Cd results exceeded the more stringent European Commission limit of 0.05 mg kg^{-1}, illustrating how compliance may vary depending on the selected benchmark. Regulatory comparisons for Cu and Cr could not be made, as Indonesian standards currently lack corresponding limits for these metals in the analyzed fish.

Low dissolved-metal concentrations do not preclude biological accumulation, as fish integrate exposure through their gills and diet over longer periods than individual water samples. The observed patterns may reflect differences in local water and sediment conditions, species physiology, body size, and feeding behavior [47, 48]. The Pb exceedances along with localized Cu enrichment in water, necessitate further analysis of sediment, fish organs, and dietary exposure. Such analyses would elucidate metal bioavailability, potential food-web transfer, and implications for ecosystem and human health.

CONCLUSION

The Otomona River generally maintained good water quality with physicochemical parameters and most dissolved metals adhering to the Indonesian Class II standards with Pollution Index values ranged from 0.63 to 0.96, while a Water Quality Index score of 70 classified the river's condition as good. Nevertheless, dissolved Cu exceeded the permissible limit at sites AP08 and AP09, and several other parameters neared their respective thresholds, underscoring the necessity for ongoing management and

monitoring. The analysis of heavy metals in aquatic biota, particularly fish, revealed bioaccumulation, notably for Cd, Cu, and Pb, despite the relatively low concentrations of heavy metals in the water column that meet quality standards. This suggests that heavy metals can accumulate through the food chain and be distributed to the tissues of aquatic biota. Consequently, fish serve as sensitive biological indicators of heavy metal pollution, highlighting potential ecological and health risks with prolonged exposure. The distribution pattern of heavy metals in water, as modeled using MIKE 21 for metals such as Cu, Pb, Hg, Cr, and Cd, indicates that concentrations are relatively low in the upstream waters of the river and increase towards the middle, downstream, and estuary. This pattern reflects the influence of anthropogenic activities along the river, although it does not reach significantly polluted levels. Thus, the river water quality remains safe for use according to its class, although the observed increasing trend necessitates continuous monitoring.

Declarations

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

RI contributed to the conceptualization, research design, data analysis, interpretation of the results, and preparation of the original manuscript. MFM contributed to field investigation, sampling, data collection, and laboratory analysis. BB contributed to data validation. MFM contributed to the modelling, visualization, and interpretation of the results. ZAH reviewed and edited the manuscript and supervised the research. All authors read and approved the final manuscript.

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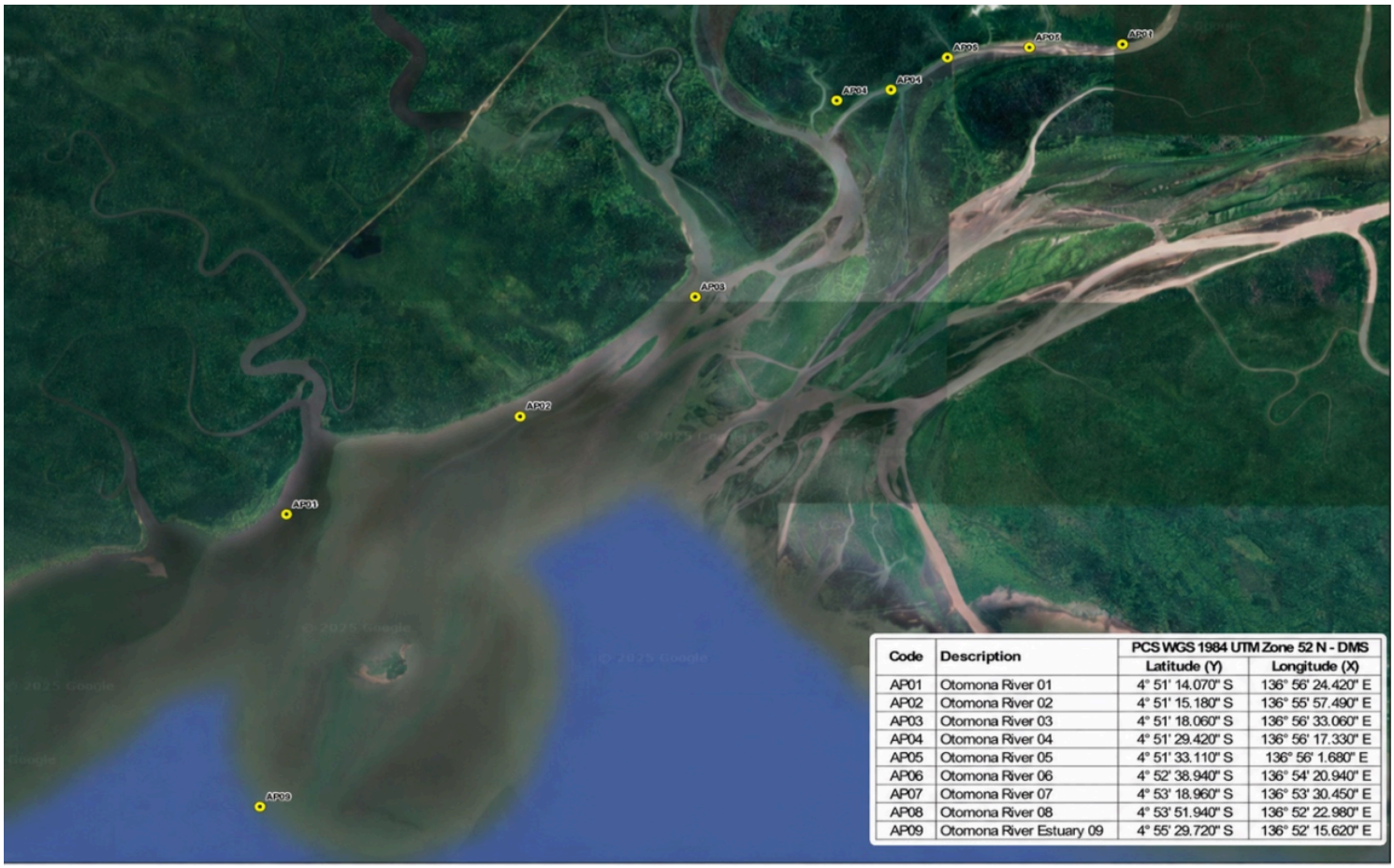
Figures



Code	Description	PCS WGS 1984 UTM Zone 52 N - DMS	
		Latitude (Y)	Longitude (X)
AP01	Otomona River 01	4° 51' 14.070" S	136° 56' 24.420" E
AP02	Otomona River 02	4° 51' 15.180" S	136° 55' 57.490" E
AP03	Otomona River 03	4° 51' 18.060" S	136° 56' 33.060" E
AP04	Otomona River 04	4° 51' 29.420" S	136° 56' 17.330" E
AP05	Otomona River 05	4° 51' 33.110" S	136° 56' 1.680" E
AP06	Otomona River 06	4° 52' 38.940" S	136° 54' 20.940" E
AP07	Otomona River 07	4° 53' 18.960" S	136° 53' 30.450" E
AP08	Otomona River 08	4° 53' 51.940" S	136° 52' 22.980" E
AP09	Otomona River Estuary 09	4° 55' 29.720" S	136° 52' 15.620" E

Figure 1

Sampling points in Otomona River

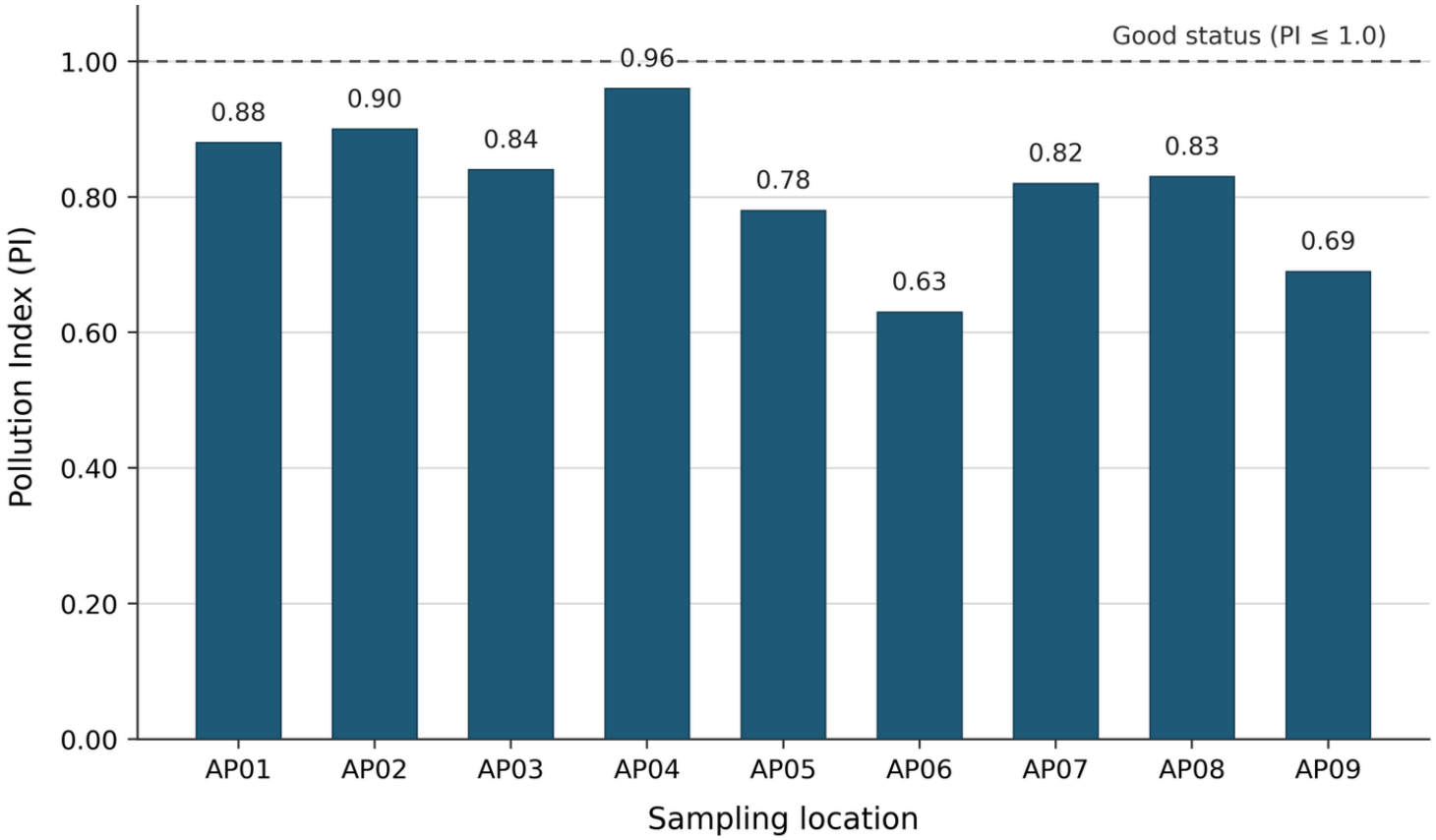


Figure 2

Pollution index by sampling location in Otomona River

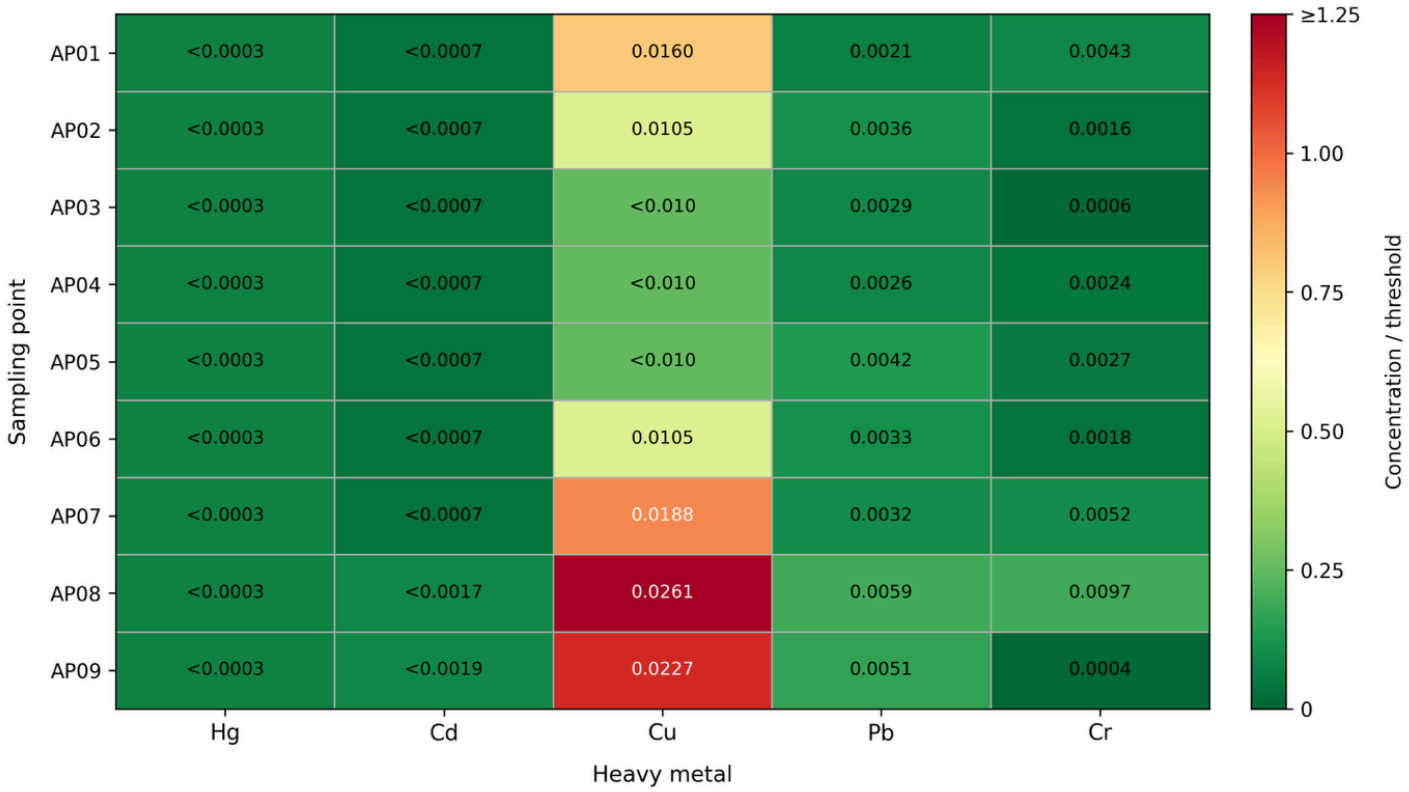


Figure 3

Heavy metal concentration in Otomona River Waters

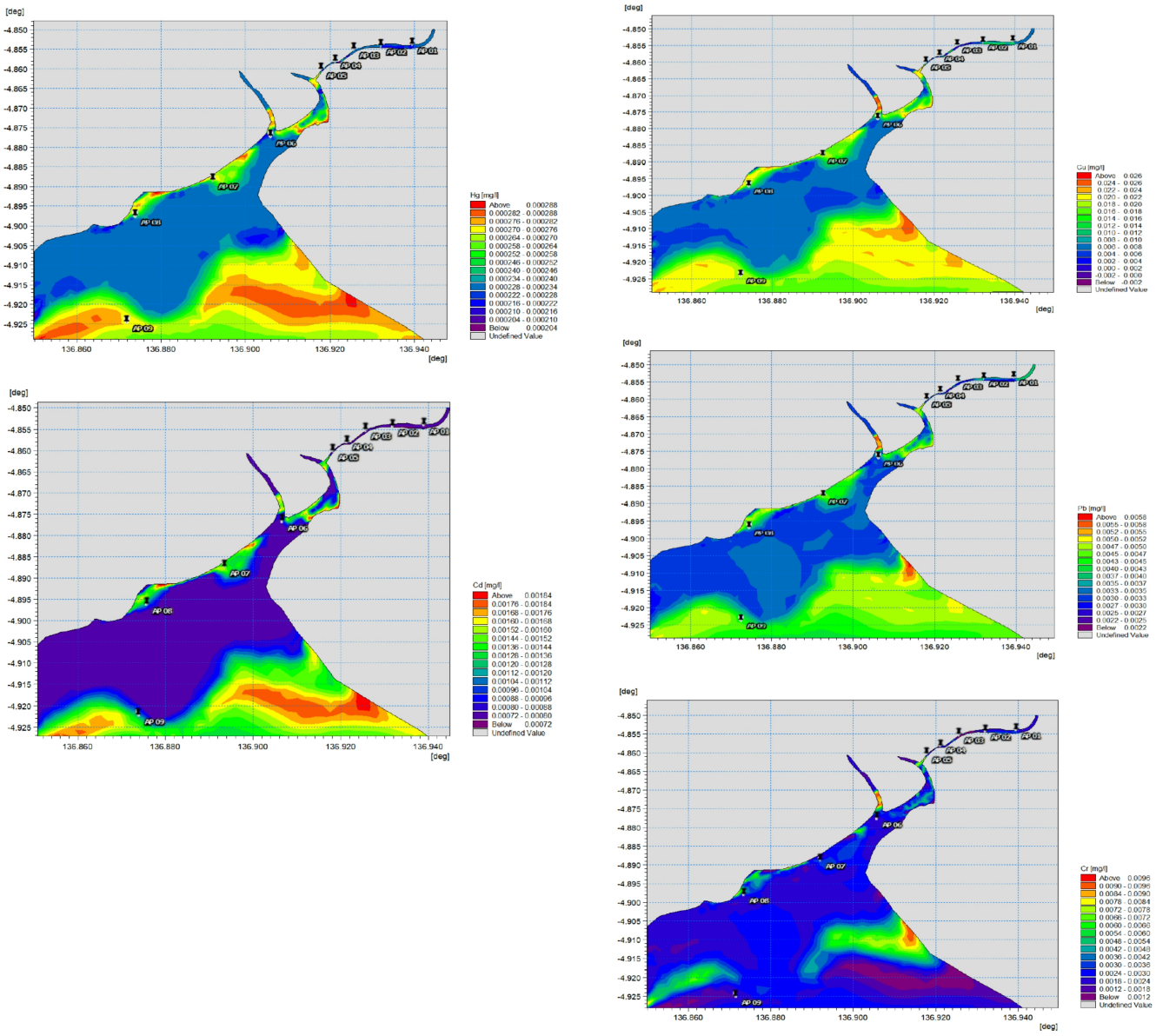


Figure 4

Distribution Pattern of (a) Hg (b) Cd (c) Cu (d) Pb (e) Cr in the Otomona River Waters