AAS-Based Multi-Media Diagnostic Approach for Evaluating Heavy Metal Contamination in the Batang Ayumi River Within the Batu Bola Landfill Influence Zone

Fatma Suryani Harahap[1*], Nurmaini Ginting[2], Heni Mulyani Pohan[1], Benny Sofyan Samosir[3]

[1] Chemistry of Education, Faculty of Teacher Training and Education, Universitas Muhammadiyah Tapanuli Selatan, Padangsidimpuan City, Indonesia.
[2] Biology of Education, Faculty of Teacher Training and Education, Universitas Muhammadiyah Tapanuli Selatan, Padangsidimpuan City, Indonesia.
[3] Mathematic of Education, Faculty of Teacher Training and Education, Universitas Muhammadiyah Tapanuli Selatan, Padangsidimpuan City, Indonesia.

Abstract: This study applies an integrated multi-media approach (river water–sediment–shallow groundwater) to assess heavy metal contamination (Pb, Cu, Cd, Fe, and Hg) along the Batang Ayumi River within the influence zone of the active Batu Bola landfill, a setting rarely evaluated in an integrated manner. Samples were collected from four stations (upstream control to downstream) and analyzed using atomic absorption spectrophotometry (AAS). Fe and Pb emerged as the most responsive indicators of landfill influence: Fe increased downstream and was reflected by accumulation in sediments, while Pb showed greater mobility in river water and nearby wells, suggesting transfer from surface transport to shallow groundwater. Cu peaked upstream, whereas Cd and Hg were relatively stable but detectable across media. Although concentrations remained below applicable standards, the spatial patterns indicate persistent environmental pressure that could intensify without improved controls. By integrating evidence across water, sediment, and groundwater, this study clarifies plausible heavy-metal migration pathways from landfill leachate — surface-water transport, sediment retention, and infiltration toward shallow aquifers — supporting targeted leachate management and long-term multi-media monitoring.

Keywords: AAS; Batang Ayumi River; Groundwater; Heavy metals; Landfill leachate; Sediment

Introduction

Urbanization and intensive land use can degrade surface- and groundwater quality (Agrawal et al., 2021). In Padangsidimpuan City, the Batang Ayumi River is a critical water body that supports community livelihoods and daily needs, including domestic use and other socio-economic activities, and it flows in close proximity to densely inhabited areas. Its importance and vulnerability are amplified by the presence of the Batu Bola Landfill (TPA) on the riverbank, where potential pollutant releases can directly affect the river system and

nearby shallow wells relied upon by residents. Previous studies indicate that open-dumping landfills lacking adequate leachate treatment can elevate heavy metal concentrations in rivers and groundwater through leachate infiltration containing organic/inorganic constituents, pathogens, and heavy metals (Fatmawinir et al., 2015; Harahap et al., 2021).

Leachate from landfills contains heavy metals such as Pb, Cu, Cd, Fe, and Hg, which are known to be toxic, persistent, and bioaccumulate in the food web (Meyrita et al., 2023). Long-term exposure to these metals can disrupt neurological function, the renal system, and the

skeletal system, and trigger neurotoxic effects at very low levels (Teng et al., 2023). When leachate seeps into the soil or is carried by surface runoff, contaminants can reach rivers and wells of residents living near landfills. This phenomenon of leachate contamination has been widely reported in Southeast Asia, especially in landfills that still use open disposal systems (Dwangga et al., 2023; Ramadan et al., 2023).

The ecological relationship between river water and sediment plays a crucial role in understanding pollution dynamics (Ouyang et al., 2018). Sediment acts as a historical reservoir for heavy metals, which can be released back into the water column when physical-chemical conditions such as pH, current, and organic matter content change (Yu et al., 2010). Therefore, multi-matrix analysis (water, sediment, and groundwater) provides a more comprehensive picture of the spatial distribution of contaminants than analysis of a single medium alone (Horowitz et al., 2017). Furthermore, the presence of shallow wells around the Batu Bola landfill increases the risk of direct exposure for the community. Shallow wells are highly susceptible to pollutant infiltration due to limited geological protection. Previous research confirms that the distance of the well from the landfill is a critical factor in determining the level of groundwater contamination by heavy metals and other hazardous compounds (Harahap et al., 2021). Therefore, monitoring well water quality is an important indicator for detecting vertical leachate migration.

A multi-media diagnostic approach that simultaneously analyzes river water, sediment, and well water is a relevant method for understanding the behavior of heavy metals in complex environmental systems such as the Batang Ayumi River. This method is able to describe the vertical and horizontal distribution patterns of contaminants and identify the processes of mobilization, deposition, and infiltration that occur. The relevance of this approach is reinforced by the use of Atomic Absorption Spectrophotometry (AAS), a high-precision analytical instrument capable of detecting heavy metals at very low concentrations according to the APHA international standards (Harahap et al., 2020; Khalifa et al., 2023). From a regional perspective, Padangsidimpuan City has experienced significant growth in domestic and economic activity, but waste management infrastructure remains limited. Many landfills in Indonesia, including the Batu Bola landfill, still operate with an open dumping system, thus creating a real and ongoing risk of environmental pollution. This underscores the importance of data-driven scientific research to understand the environmental impacts (Wahyuni et al., 2023).

The novelty of this research lies in the simultaneous application of a multi-media diagnostic approach based on AAS to three environmental compartments: river water, sediment, and groundwater to map heavy metal contamination patterns from upstream to downstream. This research is also the first to explicitly trace the hydrological relationship between the river, landfill, and wells in the Batu Bola landfill area, resulting in a more accurate scientific mapping of the direction of contaminant migration.

This research provides a critical scientific basis for formulating regional policies, particularly in evaluating landfill management, improving leachate treatment systems, and protecting the quality of groundwater used by the community. By combining a multi-media approach and high-precision analytical instruments, this study aims to close the knowledge gap regarding heavy metal dynamics in the Batang Ayumi River and provide a strong foundation for long-term mitigation.

Method

This study used a multi-media diagnostic approach to assess the heavy metal content of Pb, Cu, Cd, Fe, and Hg in three environmental compartments: river water, sediment, and well water in the Batang Ayumi River area within the Batu Bola landfill influence zone (Ali et al., 2022). This approach was chosen to provide a comprehensive overview of the mobility, accumulation, and flow patterns of heavy metals both horizontally from upstream to downstream and vertically from the surface to shallow aquifers.

Research Location and Sampling Design

The study site included four stations purposively determined based on their proximity to the landfill: an upstream station as a control site, a station directly adjacent to the landfill, a station after the landfill to assess post-exposure concentration changes, and a downstream station to identify accumulative conditions. Coordinate measurements were conducted using GPS with an accuracy of <5 meters, while physical characteristics of the river, such as current speed, depth, and surrounding conditions, were recorded as supporting data for interpreting pollution patterns. The selection of community wells followed the criteria of a distance of <200 meters from the landfill, a depth of <20 meters, and active use by the community, with records of well construction conditions and indications of groundwater flow direction.

Sampling of River Water, Sediment and Well Water

River water samples were collected. Samples were taken at a depth of 20–30 cm to avoid surface films and floating materials. Three sampling points at each station were then mixed into a single composite sample to increase representativeness. The polyethylene bottles used were cleaned and acidified, and all samples were

preserved using concentrated HNO₃ to a pH <2 before being stored in a cool box at 4°C and analyzed within 48 hours. River sediment was collected using an Ekman Grab Sampler in areas with fine material deposition. Samples were dried at 60°C to constant weight, then sieved using the <63 μm fraction, which generally contains higher metal concentrations. Sediment preparation was carried out through wet digestion using a mixture of HNO₃ and HClO₄ until the solution became clear, indicating the completion of the metal extraction process (Agha et al., 2022).

Well water samples were collected after pumping for 3–5 minutes to ensure the water collected was representative of the aquifer, not static water. Samples were preserved with concentrated HNO₃ to a pH <2 and stored at low temperature until analysis. Information related to well characteristics such as depth, well wall type, and casing condition was collected and the distance to the landfill was recorded to help assess the risk of leachate infiltration into groundwater.

Heavy Metal Analysis Using AAS

Heavy metal analysis was performed using Atomic Absorption Spectrophotometry (AAS), which has high sensitivity and is capable of detecting metals in a very low concentration range. The analysis process began with instrument calibration using standard solutions with a concentration range of 0.001–1 ppm and a calibration curve linearity requirement of $R^2 \geq 0.995$. Water samples were filtered using a Whatman 0.45 μm filter and analyzed directly or diluted if close to the

upper limit of the standard curve. Meanwhile, sediment samples that had undergone wet digestion were measured following standard AAS operating procedures. Measurements were performed in triplicate to ensure precision, and a spike recovery test was used to verify no metal loss during the preparation process. The detection limit was recorded for each metal as a basis for data interpretation (Aquisman et al., 2019).

Data Analysis and Statistics

All measurement data were analyzed using descriptive statistics to obtain minimum, maximum, mean, and standard deviation values. Spatial analysis was conducted to compare differences in metal concentrations between upstream, midstream, and downstream stations while identifying flow and accumulation patterns. Data interpretation was based on national quality standards, namely Government Regulation 22/2021 for river water quality and Minister of Health Regulation 492/2010 for drinking water quality. Furthermore, inter-media relationships were analyzed to assess the link between water contamination and the impact of the metal concentrations on the water quality. River sedimentation, sediment accumulation, and infiltration into well water. Diagnostic evaluation was used to interpret potential pollution sources and heavy metal migration directions based on a multi-compartment approach. This integrative method allows for more precise mapping of the Batu Bola landfill's impact on environmental conditions and long-term contamination risks (Iresha et al., 2024).
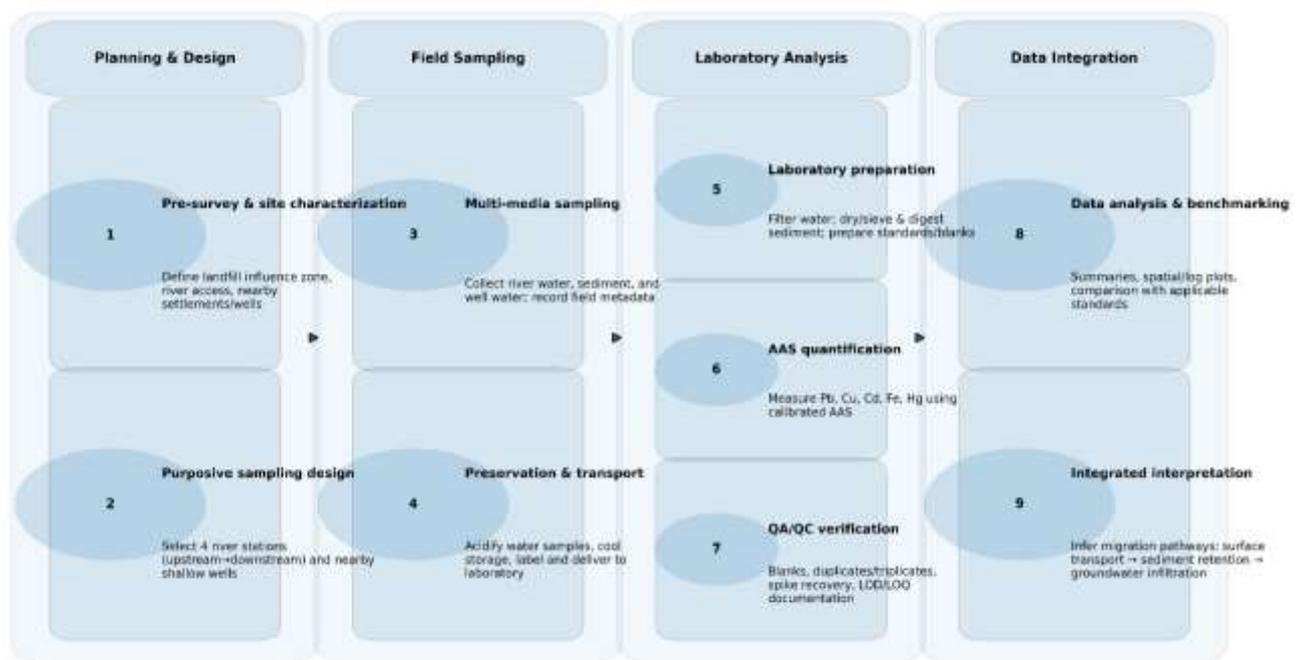
Figure 1. Research flow for integrated multi media heavy metal assessment

Result and Discussion

Analysis of heavy metal concentrations in river water, river sediment, and well water around the Batu Bola landfill showed clear spatial variations between stations. Measurements using AAS provided high sensitivity in distinguishing concentration differences between locations, both in the ppm and sub-ppm order. The measurement results are presented in three subsections: river water, sediment, and well water.

Concentration of Heavy Metals in River Water

River water measurements showed variations in concentrations between stations for all metals. Cu had the highest value at Station 1 at 0.0422 ppm, while Fe reached its maximum at Station 2 (0.059 ppm). Hg concentrations remained stable at 0.0005 ppm for all stations.

Table 1. Heavy Metal Concentration in River Water (ppm)

Station	Cu	Pb	Cd	Fe	Hg
1	0.0422	0.002	0.002	0.003	0.0005
2	0.0003	0.004	0.002	0.059	0.0005
3	0.0200	0.001	0.002	0.001	0.0005
4	0.0003	0.001	0.002	0.051	0.0005

Table 2. Descriptive Statistics of River Water

Metal	Mean	Min–Max	SD
Cu	0.0157	0.0003–0.0422	0.0191
Pb	0.0020	0.001–0.004	0.0012
Cd	0.0020	0.002–0.002	0.0000
Fe	0.0285	0.001–0.059	0.0296
Hg	0.0005	0.0005–0.0005	0.0000

Heavy Metal Concentration in River Sediment

Sediment showed a different distribution pattern than river water, especially for Fe and Cu. Fe increased gradually from upstream to downstream, reaching its highest value at Station 4 (0.04 ppm).

Table 3. Heavy Metal Concentration in Sediment (ppm)

Station	Cu	Pb	Cd	Fe	Hg
1	0.003	0.002	0.0003	0.020	0.0004
2	0.005	0.001	0.0030	0.030	0.0004
3	0.005	0.001	0.0003	0.030	0.0004
4	0.003	0.001	0.0030	0.040	0.0004

Table 4. Descriptive Statistics of Sediment

Metal	Mean	Min–Max	SD
Cu	0.0040	0.003–0.005	0.0010
Pb	0.0013	0.001–0.002	0.0005
Cd	0.00165	0.0003–0.0030	0.0014
Fe	0.0300	0.020–0.040	0.0082
Hg	0.0004	0.0004–0.0004	0.0000

Heavy Metal Concentration in Well Water

Well water exhibits a variation pattern that follows the direction of groundwater flow from the landfill downstream. The highest Cu levels were found at Station 3 (0.008 ppm), while Pb and Fe levels gradually increased towards Station 4.

Table 5. Heavy Metal Concentration in Well Water (ppm)

Station	Cu	Pb	Cd	Fe	Hg
1	0.005	0.001	0.0030	0.030	0.0004
2	0.005	0.001	0.0005	0.030	0.0004
3	0.008	0.003	0.0030	0.020	0.0002
4	0.005	0.004	0.0003	0.030	0.0002

Table 6. Descriptive Statistics of Well Water

Metal	Mean	Min–Max	SD
Cu	0.00575	0.005–0.008	0.0013
Pb	0.00225	0.001–0.004	0.0015
Cd	0.00195	0.0003–0.0030	0.0013
Fe	0.0275	0.020–0.030	0.0050
Hg	0.00030	0.0002–0.0004	0.0001

Cu (Copper)

Station 1 showed the highest Cu concentration (0.0422 ppm), exceeding the 0.02 ppm standard. The graph shows a drastic decrease at Stations 2 and 4 (0.0003 ppm), then a rise again at Station 3 (0.02 ppm). This pattern suggests that Cu does not originate predominantly from the landfill, but likely from domestic/agricultural activities upstream, as well as remobilization at Station 3, where the water flow is more turbulent.

The sediment results show that Cu peaked at Stations 2 and 3 (0.005 ppm), i.e., closest to and immediately downstream of the landfill. This pattern aligns with evidence that aquatic sediments commonly function as sinks for heavy metals, and that Cu tends to partition strongly onto fine particles and organic-rich solid phases—so elevated sediment Cu can occur even when dissolved Cu in the overlying water (e.g., Station 2) remains low (Chon et al., 2012). Such "storage" in sediments may reflect chronic inputs and can also mask short-term signals in the water column while still indicating anthropogenic pressure, with the potential for remobilization under changing pH/redox conditions (Algül et al., 2020). The well-water results complement this horizontal (river–sediment) signal by suggesting vertical transfer: the highest Cu in wells occurred at Station 3 (0.008 ppm), consistent with studies showing that leachate percolation from active landfills can contaminate nearby shallow groundwater (Huang et al., 2024). Although Cu remains below the drinking-water guideline value (2 mg/L), the localized increasing pattern supports a measurable anthropogenic influence and strengthens the interpretation of plausible

migration pathways—from surface transport, to sediment retention, and infiltration toward shallow aquifers.

Figure 2. Concentration trend of Cu

Pb (Lead)

The concentration of Pb in river water increased significantly at Station 2 (0.004 ppm), twice as high as at Station 1 (0.002 ppm). Although still below the quality standard (0.01 ppm), the graph shows a pattern consistent with the presence of the landfill, where Station 2 is a potential zone of direct contact with leachate. In river sediments, Pb metal was higher at Station 1 (0.002 ppm) and tended to decrease at other stations (0.001 ppm). This indicates that Pb is more easily released into the water column in areas near the landfill and does not settle much in the sediment. The highest Pb concentration in well water was at Station 4 (0.004 ppm). The gradual increase from Station 1 → 4 reflects the movement of groundwater mass from the direction of the landfill towards downstream settlements. Although below the threshold (0.01 ppm), long-term accumulation can be dangerous.

Figure 3. Concentration trend of Pb

Cd (Cadmium)

The concentration of Cd in river water was relatively uniform at all stations (0.002 ppm). When compared to the Cd quality standard (0.005 ppm), all values were well below the threshold. However, consistent Cd levels indicate that this metal is evenly distributed and mobile in river water. Meanwhile, the highest Cd levels in sediment were at Stations 2 and 4 (0.003 ppm). The increase at these two locations corresponds to the contamination pattern from leachate deposited in areas with slower flow. The concentration of the heavy metal Cd in well water varied (0.0003–0.003 ppm), with the highest values at Stations 1 and 3 (0.003 ppm). Generally still below the standard, but Cd has acute toxic effects even in small amounts.
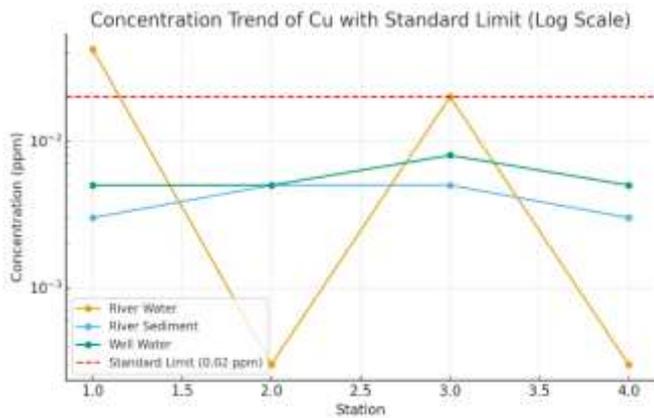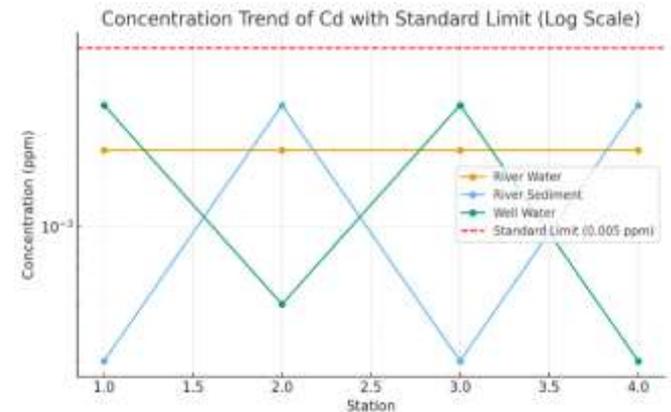

Figure 4. Concentration trend of Cd

Fe (Iron)

Fe is the metal that most strongly indicates the influence of the landfill. Fe levels in river water rose dramatically at Station 2 (0.059 ppm) and remained high at Station 4 (0.051 ppm). Although still below the quality standard (0.3 ppm), the graph pattern confirms that Fe originates from landfill leachate, is carried downstream by the river, and temporarily decreases at Station 3 (flow segmentation).
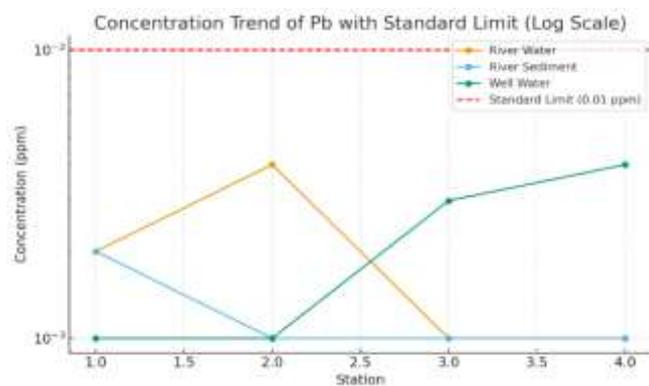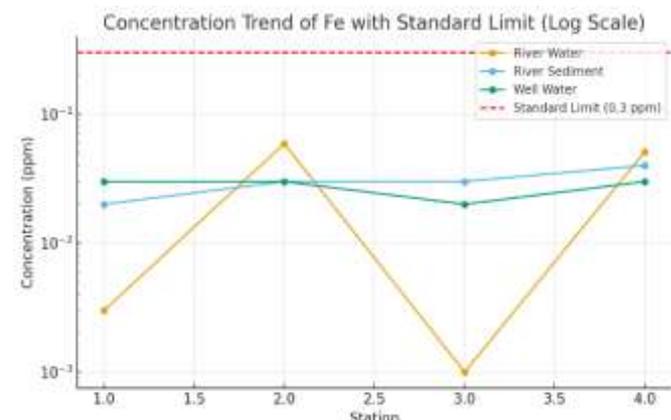

Figure 5. Concentration trend of Fe

Meanwhile, in river sediments, Fe metal increases consistently from upstream (0.02 ppm) to downstream (0.04 ppm). The line graph shows a linear increase,

indicating the transport of Fe with suspended particles along the river flow. The results of the analysis in well water Fe values are relatively high (0.02–0.03 ppm) but still below the quality standard (0.3 ppm). The relatively stable pattern indicates that the geological characteristics of the aquifer also play a role.

Hg (Mercury)

The Hg concentration in river water was stable at all stations (0.0005 ppm) and still below the quality standard (0.001 ppm). The stability of Hg reflects its presence in the form of organic complexes that tend to dissolve and are not easily adsorbed in sediment. Meanwhile, in river sediment, Hg was relatively constant at all stations (0.0004 ppm), reflecting Hg's tendency to form stable complexes in the organic fraction of sediment. In well water, Hg values were very low (0.0002–0.0004 ppm), but remained present in all wells. This indicates the ability of mercury to migrate in the form of dissolved complexes.
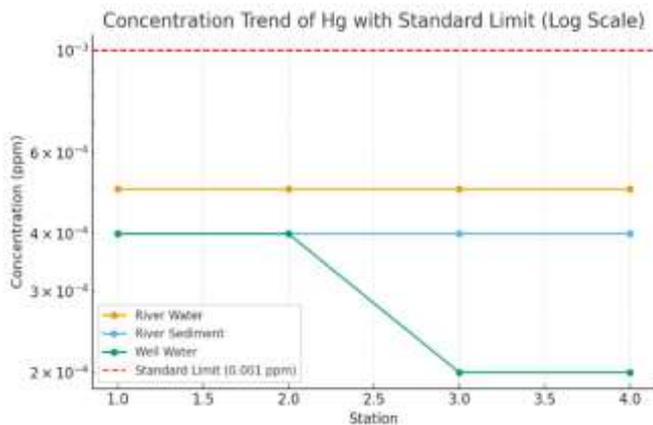

Figure 6. Concentration trend of Hg

An integrated analysis of three environmental media river water, sediment, and well water reveals heavy metal distribution patterns consistent with the influence of persistent pollutant sources such as open dumping. This multi-media approach broadens our understanding of the dynamics of contaminant mobility, deposition, and infiltration in the Batang River system Ayumi, as recommended in modern environmental studies that emphasize the importance of ecological compartment integration (Sari et al., 2023).

The distribution of Fe in river water showed a significant increase at Stations 2 and 4, indicating metal input from Batu Bola Landfill leachate. Fe dissolved in the reductive conditions of leachate is then oxidized in the river flow and forms $Fe(OH)_3$ deposits that can accumulate in sediments. This is consistent with the discovery of the highest Fe concentrations in downstream sediments, illustrating metal transport that

follows the movement of suspended material (Harahap et al., 2018; Setyono et al., 2024).

The concentration of Cu exhibited distinct characteristics compared to other metals, with the highest value at Station 1, far from the landfill. This finding indicates that the source of Cu pollution is not the landfill, but rather upstream activities such as the use of Cu-based pesticides or domestic waste. However, the increase in Cu in the sediment at Stations 2 and 3 indicates that this metal continues to interact with fine particles and is strongly adsorbed in the organic fraction of the sediment, thus remaining part of the local pollution signal (Hall et al., 2022).

The behavior of Pb in river water differs from that of Cu, indicated by an increase at Station 2, close to the landfill. This is consistent with Pb's ability to readily form complexes with humates in leachate, making it mobile in the water column (Botero et al., 2014). In sediment, Pb was actually higher at Station 1, indicating that Pb in the area near the landfill is more dominant in the dissolved phase than in the sedimented phase. This pattern often occurs in rivers receiving leachate loads due to the high content of organic compounds that dissolve metals (Sayadi et al., 2015).

Cd exhibited high mobility characteristics, with relatively stable concentrations in river water but increasing in sediments at Stations 2 and 4. The close association of Cd with Fe in the sediments supports the suggestion of Cd co-precipitation with Fe oxides, a geochemical mechanism widely described in the sediment literature. This suggests that although Cd did not show a significant spike in water, its pollution signal was still recorded in the sediments (Li et al., 2018). The stability of Hg concentrations in river water (0.0005 ppm) and sediment (0.0004 ppm) indicates that Hg is present in relatively geochemically stable chemical forms, such as organo-mercury complexes or Hg^{2+} ions bound to organic matter. Although not a strong indication of landfill origin, the presence of Hg in well water suggests that Hg is capable of migrating to shallow aquifers, in line with its tendency to readily form dissolved complexes.

Well water around the landfill showed contamination patterns very close to those of river water, particularly for the metals Cu, Pb, and Fe. This suggests a hydrological connection between surface flow and shallow aquifers, where leachate infiltration can follow the path of soil fractures or pores in highly permeable soils. The fact that Pb in well water increasing progressively downstream strengthens the hypothesis that the hydraulic gradient facilitates the movement of contaminants from the landfill towards settlements.

The stable Fe concentration in well water indicates changes in the redox conditions in the aquifer due to the influx of organic matter from leachate. This reductive

environment can dissolve Fe from local geological materials, illustrating the phenomenon of secondary mobilization that often occurs in contaminated groundwater systems (Cozzarelli et al., 2016). This suggests that landfills are not only a direct source of metals but also trigger chemical changes that accelerate their release from the local geology. Cd in well water exhibits a pattern not entirely related to landfills, with high values at Stations 1 and 3. This finding suggests that

in addition to landfills, there are additional sources of contamination such as battery residue or domestic waste. The high mobility of Cd strengthens the possibility that Cd moves through various environmental entry pathways (Qadriyah et al., 2019), necessitating improved domestic waste management policies. To clarify the relationships between media and stations, a heatmap of heavy metal concentrations was used as an integrative visual tool.
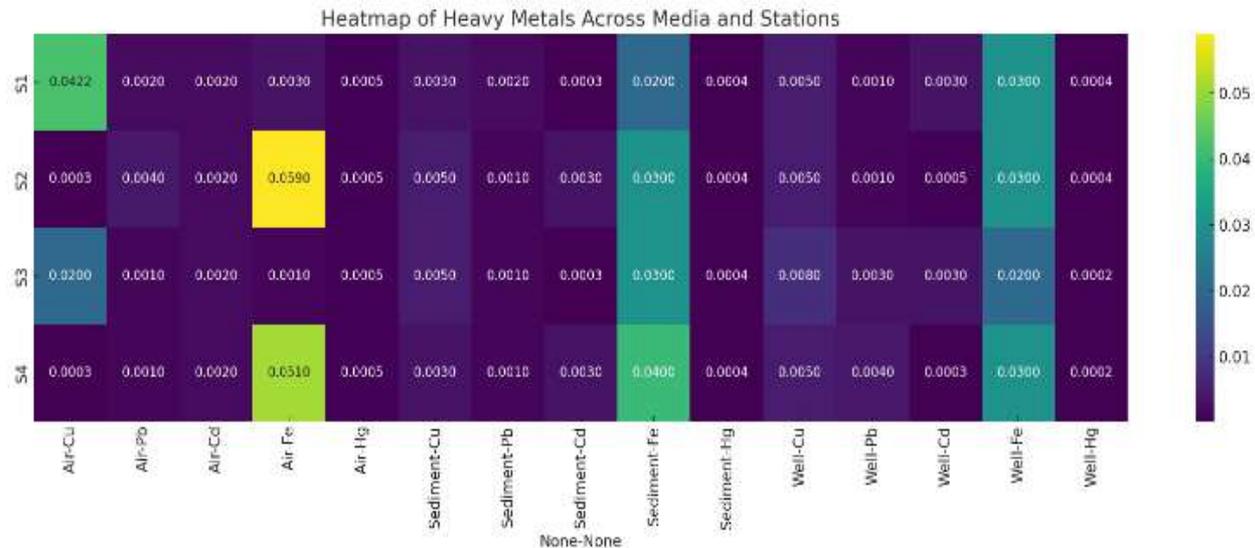

Figure 7. Heatmap of heavy metals across media and stations

This heatmap shows that Fe and Cd exhibit strong accumulative patterns in sediment, while Pb exhibits high mobility in river water and well water. Hg appears stable throughout the medium, while Cu exhibits a mixed pattern between upstream sources and local adsorption (Bao et al., 2024). These patterns support the interpretation that the Batu Bola landfill significantly contributes to the dynamics of certain metals, particularly Fe and Pb, in the river system. The logarithmic graphs used in the river water, sediment, and well analyses further emphasize the order-of-magnitude differences in concentrations between metals. This visualization is important when dealing with heavy metals that have very narrow concentration ranges but have significant impacts on ecosystem health. The logarithmic scale facilitates the identification of subtle trends, particularly for metals like Hg and Cd, whose differences are not visible on a linear scale. From an ecotoxicological perspective, elevated Fe and Pb levels near the landfill can pose a risk to aquatic biota, particularly benthic organisms. High levels of Fe can disrupt respiration of underwater organisms, while Pb is known to be neurotoxic even at low concentrations. Cd and Hg are potentially involved in bioaccumulation and biomagnification processes, so long-term exposure

can affect human health and ecosystems (Yang et al., 2022).

Comparison with national quality standards shows that although most metals remain within safe limits based on Government Regulation 22/2021 and Minister of Health Regulation 492/2010, the pattern of increasing metal concentrations indicates a potential cumulative risk. Many studies have shown that chronic exposure at low concentrations remains hazardous, especially for Pb, Cd, and Hg (Komala et al., 2021). The hydrological relationship between the river, landfill, and wells indicates a clear contaminant migration pathway. The increase in metals in downstream well water indicates that the landfill is located in a vulnerable hydrogeological zone. Leachate can seep through porous soil and reach shallow aquifers, then move along the hydraulic gradient toward residential areas. These findings are consistent with studies of landfills in various developing countries (Koutsopoulou et al., 2017).

The AAS-based multi-media approach used in this study provides a strong scientific basis for detecting complex pollution patterns. AAS has high sensitivity down to sub-ppm levels, enabling it to capture small, ecologically important variations between stations (Manullang et al., 2017). The consistent pattern of metal

elevations across specific media validates the hypothesis that the Batu Bola Landfill is a major contributor to pollution in the surrounding river and well water areas. Overall, the integration of river water, sediment, and well water data demonstrates significant environmental stress associated with the presence of the Batu Bola Landfill. Although heavy metal concentrations remain within safe limits, distribution patterns consistent with river and groundwater flow indicate that pollution is chronic and has the potential to escalate if no mitigation measures are taken. These findings provide an important foundation for the implementation of improved leachate treatment systems, the development of geohydrological buffer zones, and ongoing monitoring to prevent long-term risks to the environment and public health (Uliya et al., 2025).

Conclusion

This study successfully revealed the distribution patterns of heavy metals in three environmental media: river water, sediment, and well water, which indicate a strong link between the environmental quality conditions of the Batang Ayumi River and the presence of the Batu Bola Landfill. The multi-media approach and the use of AAS enabled more accurate and integrative detection of contamination patterns, thus providing a comprehensive picture of the geochemical dynamics of metals in the aquatic and groundwater systems in the study area. The results showed that Fe and Pb were the most consistent indicators of the influence of the landfill. The significant increase in Fe in river water at Stations 2 and 4, as well as the accumulation of Fe in downstream sediments, indicated the presence of metal supply from leachate and the repeated oxidation-precipitation process. Pb showed high mobility in river and well water, reflecting its presence in the dissolved phase following river flow and infiltration into shallow aquifers. Cu showed a distinct contamination pattern, with the highest concentrations in the upstream section, indicating a source of contamination outside the landfill. However, the increase in Cu in midstream sediments indicates that this metal continues to experience local adsorption from anthropogenic activities around the landfill. Cd showed a tendency to follow the distribution of Fe in the sediment, while Hg remained stable in all media but showed the ability to migrate vertically to well water. The integration of the results from the three media confirmed the hydrological relationship between the river, the landfill, and shallow groundwater. The increase in metals in downstream wells indicated that leachate infiltration has the potential to reach aquifers used by the community. Although heavy metal concentrations in all media remained within safe limits based on national quality standards, the increasing

pattern at several stations indicated potential environmental and health risks if exposure persists chronically. Overall, this study confirms that the presence of the Batu Bola landfill has a significant impact on heavy metal dynamics in the Batang Ayumi River and its surrounding environment. These findings emphasize the need for better leachate management, improved hydrogeological protection systems, and routine multi-media monitoring to prevent increased risks of future pollution.

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