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Hydrogeochemical and spatial assessment of landfill-associated groundwater contamination in a tropical megacity

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ABSTRACT

Municipal landfills in rapidly urbanizing tropical cities represent major sources of groundwater contamination, yet integrated hydrogeochemical and spatial risk assessments in developing countries remain limited. This study evaluates groundwater contamination and associated human health risks around the Tamangapa landfill in Makassar, Indonesia, using an integrated framework combining hydrochemical analysis, multivariate statistics, geospatial modeling, and risk assessment. Groundwater samples from 36 monitoring wells were analyzed for physicochemical parameters and heavy metals, particularly hexavalent chromium [Cr(VI)] and iron (Fe). Spatial interpolation using inverse distance weighting (IDW) and principal component analysis (PCA) were applied to identify contamination patterns and dominant controlling factors. The results revealed that Fe concentrations exceeded drinking water standards in 80.8% of wells, while Cr(VI) exceeded permissible limits in 40% of sampling points. Contamination hotspots were concentrated north of the landfill, consistent with regional groundwater flow direction. Exploratory PCA analysis identified three principal covariance structures associated with groundwater contamination variability, interpreted as potential landfill-related hydrochemical influence, hydrogeochemical control conditions, and secondary anthropogenic associations. Exponential decay modeling showed that Fe contamination extended up to 4 km from the landfill, exceeding the conventional 1 km regulatory buffer and indicating higher contaminant mobility under tropical hydrogeological conditions. Human health risk assessment indicated that children living within the 1 km exposure zone faced significant non-carcinogenic risk (HI > 1), while carcinogenic risk from Cr(VI) exceeded acceptable thresholds in several locations. The findings indicate that tropical landfill systems may generate broader groundwater contamination plumes than those commonly reported in temperate regions, although the spatial extent identified in this study should be interpreted within the limitations of the sampling density and seasonal coverage. The findings suggest that groundwater contamination surrounding tropical landfill systems may extend beyond commonly applied regulatory monitoring distances under certain hydrogeological conditions. This study provides an integrated preliminary scientific basis for improving landfill monitoring, revising buffer-zone policies, and strengthening groundwater protection strategies in tropical megacities.

Keywords: landfill contamination, groundwater pollution, hydrogeochemistry, spatial risk assessment, tropical megacity, principal component analysis, groundwater plume, human health risk.

INTRODUCTION

Municipal solid waste (MSW) landfills have become one of the most significant anthropogenic sources of environmental degradation in rapidly urbanizing regions worldwide. Increasing waste generation driven by population growth, industrialization, and urban expansion has intensified pressure on landfill systems, particularly in developing countries where waste management infrastructure remains inadequate (Satria et al., 2025; Hamzah et al., 2025; Darhamsyah et al., 2025). Landfill leachate contains complex mixtures of dissolved organic matter, nutrients, pathogens, and heavy metals that can infiltrate surrounding soil and groundwater systems (Alao, 2025; Abdel-Shafy et al., 2024; Gupta et al., 2024). Previous studies have shown that uncontrolled landfill operations may significantly alter groundwater hydrochemistry and pose serious ecological and human health risks (Alao et al., 2024; Alimuddin et al., 2026; Alao, 2025 Lantang et al., 2025; Alao et al., 2023). In addition, greenhouse gas emissions and long-term contaminant persistence further position landfills as critical environmental challenges in the Anthropocene era (Manheim et al., 2024; Weber et al., 2025; Brand and Spencer, 2024). Although groundwater contamination associated with landfill activities has been extensively studied in temperate countries, investigations in tropical developing regions remain comparatively limited.

Groundwater contamination in tropical urban environments presents unique hydrogeochemical characteristics compared to temperate systems. High annual rainfall, elevated temperatures, shallow aquifer systems, and permeable alluvial deposits accelerate leachate generation and contaminant migration (Majee et al., 2026; Rajan et al., 2024; Lekshmy and Achari, 2026). Studies conducted in Europe and North America generally reported contamination plumes confined within 0.5–1 km from landfill boundaries due to engineered containment systems and lower recharge rates (Abiriga et al., 2021; Roy et al., 2025). In contrast, tropical landfill systems often operate under open dumping conditions with limited leachate management, potentially resulting in broader contaminant dispersion. Several studies conducted in tropical and humid environments have suggested that high rainfall intensity, shallow groundwater systems, and limited landfill engineering may enhance contaminant migration potential compared with some temperate landfill settings. However, plume behavior remains strongly influenced by site-specific hydrogeological conditions, landfill design, and local groundwater flow characteristics (Lindamulla et al., 2022; Mishra et al., 2019). Similarly, Hammash and Abed (2022) observed elevated heavy metal concentrations in groundwater surrounding unlined landfill systems in Iraq. However, comprehensive hydrogeochemical and spatial risk assessments integrating contaminant transport, multivariate statistics, and human exposure analysis remain scarce in Southeast Asian megacities.

Several previous studies have focused primarily on isolated aspects of landfill pollution, including heavy metal concentration analysis, methane emission estimation, or groundwater quality indexing. For example, Lando et al. (2021) investigated methane emissions from the Tamangapa landfill using the IPCC waste model, while Artiningsih et al. (2019) examined mercury distribution surrounding the same landfill system. Other studies in Indonesia mainly emphasized environmental monitoring without integrating hydrochemical interpretation and spatial risk modeling (Ramadhan, 2025; Basuki et al., 2022). Internationally, many investigations employed descriptive statistical approaches without incorporating multivariate analysis capable of identifying dominant contamination drivers and hydrogeochemical interactions (Zuffianò et al., 2018). Furthermore, regulatory buffer zones are frequently established using generalized assumptions rather than empirical plume validation based on groundwater flow dynamics. As a result, existing management frameworks may underestimate the actual extent of groundwater contamination in tropical landfill environments.

The Tamangapa landfill in Makassar City, Indonesia, represents a critical case study for understanding landfill-induced groundwater contamination in tropical megacities. Operating since 1993, the landfill currently receives approximately 600–800 tons of municipal waste per day and has exceeded its design capacity in recent years. The landfill is situated within a tropical monsoonal climate characterized by annual rainfall exceeding 2.500 mm and shallow unconfined aquifers that facilitate contaminant migration. Preliminary investigations reported elevated concentrations of iron and chromium in surrounding groundwater systems. However, the spatial extent, controlling hydrogeochemical processes, and associated human health risks have not yet been comprehensively evaluated. Moreover, there remains limited understanding of whether the observed contamination plume exceeds Indonesia's conventional 1 km landfill buffer regulation.

Therefore, this study aims to evaluate groundwater contamination patterns and associated health risks surrounding the Tamangapa landfill using an integrated hydrogeochemical and spatial risk assessment framework. Specifically, this study combines hydrochemical characterization, PCA, geospatial interpolation, and deterministic risk assessment to identify dominant contamination drivers, delineate plume migration, and quantify population exposure. Unlike previous studies that focused on single environmental components, this research integrates hydrogeochemical interpretation with spatial risk analysis and human health assessment within a unified analytical framework. The study also contributes empirical evidence regarding tropical amplification of landfill contamination and the inadequacy of fixed regulatory buffer zones under tropical hydrogeological conditions. The findings are expected to support evidence-based landfill management policies and groundwater protection strategies for rapidly urbanizing tropical cities.

Despite the integrated analytical approach applied in this study, several limitations should be acknowledged from the outset. The groundwater sampling design represents a moderate-density monitoring network constrained by field accessibility, community permission, and laboratory resources. In addition, groundwater sampling was conducted during a single hydrological season, which may not fully capture temporal variations associated with seasonal recharge and contaminant transport dynamics. Therefore, the findings should be interpreted as a spatially integrated assessment of prevailing contamination conditions rather than a complete representation of long-term hydrogeochemical variability. Nevertheless, the study provides important baseline evidence regarding landfill-induced groundwater contamination under tropical hydrogeological conditions where monitoring data remain limited.

RESEARCH METHODS

Study area

This study was conducted at the Tamangapa Landfill (Antang Landfill), located in Manggala District, Makassar City, South Sulawesi Province, Indonesia. The landfill has operated since 1993 and functions as the primary municipal solid waste disposal facility for Makassar City. The site occupies approximately 19.1 ha and receives an estimated 600–800 tons of municipal waste daily. The landfill currently operates under a transitional open-dumping system with limited leachate management and without fully engineered liner infrastructure.

Makassar City experiences a tropical monsoonal climate characterized by annual rainfall exceeding 2.500 mm and average temperatures ranging from 27–32 °C. These climatic conditions accelerate waste decomposition and increase leachate production. Hydrogeologically, the study area is dominated by shallow alluvial aquifers composed of unconsolidated sand and gravel deposits with relatively high hydraulic conductivity. Groundwater flow is predominantly directed northward, increasing the vulnerability of settlements located downgradient of the landfill. The geographical location of the study area and groundwater sampling points are presented in Figure 1.

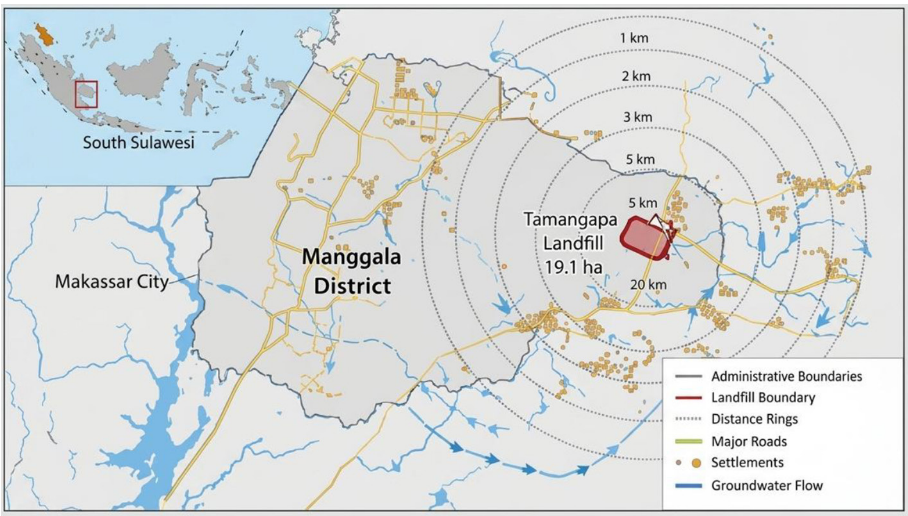

Figure 1. Location of the Tamangapa landfill and distribution of groundwater monitoring wells in Makassar City, Indonesia

Research design and analytical framework

This study employed an integrated hydrogeochemical and spatial risk assessment framework to evaluate groundwater contamination associated with landfill activities. The analytical framework combined field sampling, laboratory analysis, multivariate statistical analysis, geospatial modeling, and human health risk assessment.

The research workflow consisted of five sequential stages: (1) groundwater sampling and laboratory characterization, (2) hydrochemical analysis, (3) statistical evaluation using PCA and correlation analysis, (4) spatial interpolation and contamination plume mapping using Geographic Information Systems (GIS), and (5) deterministic human health risk assessment. A schematic representation of the integrated analytical framework is shown in Figure 2.

In addition to the hydrogeochemical and statistical analyses, the study adopted a Source–Pathway–Receptor–Impact–Mitigation (SPRIM) conceptual framework to synthesize environmental processes and management implications associated with landfill-induced groundwater contamination. The SPRIM framework was used qualitatively to integrate contamination sources, migration pathways, exposed receptors, environmental impacts, and potential mitigation strategies within the context of tropical landfill systems.

Groundwater sampling and laboratory analysis

Sampling Strategy

Groundwater samples were collected from 36 monitoring wells surrounding the Tamangapa landfill, consisting of 10 wells for hexavalent chromium [Cr(VI)] analysis and 26 wells for total iron (Fe) analysis. Sampling locations were selected based on several considerations, including distance from landfill boundaries, regional groundwater flow direction, population density distribution, and accessibility as well as community permission. To evaluate contamination gradients spatially, the wells were classified into five distance-based zones: 0–1 km, 1–2 km, 2–3 km, 3–4 km, and >4 km from the landfill boundary. Groundwater sampling was conducted during the dry season to minimize dilution effects associated with rainfall infiltration and to represent peak contamination conditions within the aquifer system. Detailed coordinates and characteristics of the monitoring wells are presented in Table 1.

The groundwater monitoring network was designed as a targeted environmental screening system intended to capture the primary down-gradient contamination gradient surrounding the landfill rather than to provide a fully exhaustive

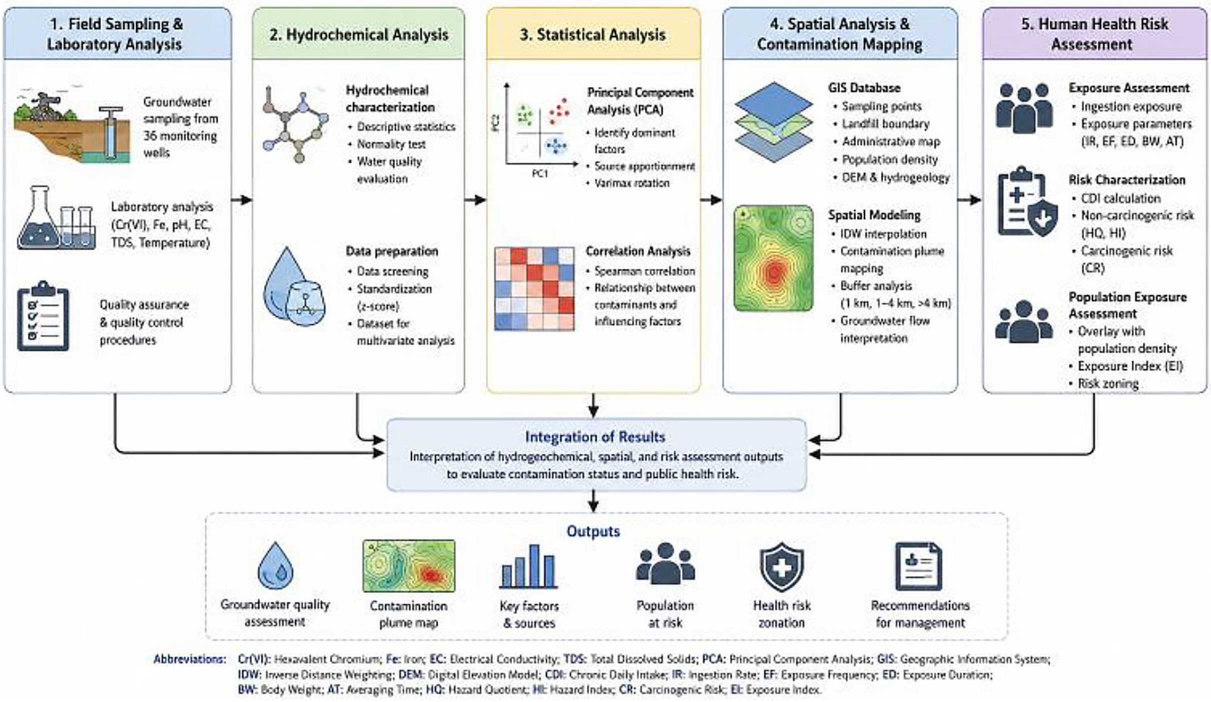

Figure 2. Conceptual framework of the integrated hydrogeochemical and spatial risk assessment approach

Table 1. Coordinates and characteristics of groundwater monitoring wells around the Tamangapa landfill

Well Code	Latitude (S)	Longitude (E)	Distance from landfill (km)	Direction from landfill	Well type	Parameter analyzed
GW-01	5°10’12.4”	119°30’45.1”	0.4	North	Dug well	Cr(VI), Fe
GW-02	5°10’18.7”	119°30’51.6”	0.6	North	Dug well	Cr(VI), Fe
GW-03	5°10’25.9”	119°30’58.3”	0.8	Northeast	Bore well	Cr(VI)
GW-04	5°10’31.5”	119°31’05.2”	1.1	North	Dug well	Fe
GW-05	5°10’39.2”	119°31’12.4”	1.4	Northeast	Dug well	Fe
GW-06	5°10’45.6”	119°31’18.9”	1.7	North	Bore well	Cr(VI), Fe
GW-07	5°10’52.1”	119°31’25.3”	2.0	North	Dug well	Fe
GW-08	5°10’58.8”	119°31’32.6”	2.3	Northeast	Dug well	Fe
GW-09	5°11’05.4”	119°31’40.1”	2.6	North	Bore well	Cr(VI)
GW-10	5°11’12.7”	119°31’46.8”	2.9	North	Dug well	Fe
GW-11	5°11’18.9”	119°31’53.5”	3.1	North	Dug well	Fe
GW-12	5°11’25.6”	119°32’00.7”	3.4	Northeast	Bore well	Cr(VI), Fe
GW-13	5°11’31.2”	119°32’06.9”	3.7	North	Dug well	Fe
GW-14	5°11’38.7”	119°32’14.3”	4.0	North	Dug well	Fe
GW-15	5°11’45.3”	119°32’20.8”	4.3	Northeast	Bore well	Cr(VI)
GW-16	5°11’52.1”	119°32’28.1”	4.7	North	Dug well	Fe
GW-17	5°11’58.4”	119°32’34.7”	5.0	North	Dug well	Fe
GW-18	5°12’05.6”	119°32’42.5”	5.3	Northeast	Bore well	Cr(VI), Fe

Note: Coordinates are presented in geographic coordinate system (WGS 84). Monitoring wells were distributed based on distance gradient, groundwater flow direction, and settlement distribution surrounding the landfill area.

hydrogeological characterization of the aquifer. Monitoring wells were selected purposively based on four principal criteria: (1) proximity to landfill boundaries, (2) inferred regional groundwater flow direction, (3) settlement distribution and groundwater utilization intensity, and (4) field accessibility and community permission. This targeted sampling approach was adopted to maximize spatial representation of potential contamination pathways under logistical and analytical constraints commonly encountered in developing urban environments.

Cr(VI) analysis was performed on a subset of 10 strategically selected wells because hexavalent chromium laboratory analysis required more complex analytical preparation, higher operational costs, and stricter preservation procedures compared with Fe analysis. Therefore, Cr(VI) measurements were prioritized in wells located along the principal downgradient groundwater flow pathway and within zones expected to exhibit the highest contamination potential based on preliminary hydrogeological observations. In contrast, Fe analysis was conducted on a larger number of wells because iron represented the dominant contaminant identified during preliminary field investigations and could be analyzed more efficiently across broader spatial coverage.

Groundwater sampling was conducted during a single dry-season monitoring campaign to minimize short-term dilution effects associated with intense rainfall and to represent relatively stable contamination conditions within the shallow aquifer system. Consequently, the present study should be interpreted as a spatially integrated assessment of prevailing contamination conditions rather than a direct evaluation of seasonal contaminant variability or long-term plume persistence. Although repeated seasonal monitoring would improve temporal characterization of contaminant transport dynamics, the current dataset provides important baseline evidence regarding landfill-induced groundwater contamination under tropical hydrogeological conditions where environmental monitoring data remain limited.

The number of monitoring wells analyzed for Cr(VI) was smaller than that used for Fe due to analytical cost constraints and prioritization of wells located along the principal downgradient groundwater flow pathway. Although the sampling density may limit high-resolution spatial generalization, the selected monitoring wells were designed to represent contamination gradients across major hydrogeological zones surrounding the landfill. The present study should therefore be interpreted as an integrated environmental screening assessment intended to identify dominant contamination patterns and potential risk zones rather than a definitive hydrogeological characterization of the entire aquifer system.

Physicochemical and heavy metal analysis

Groundwater samples were collected using acid-washed polyethylene bottles following APHA standard procedures. Samples designated for heavy metal analysis were preserved by acidification with concentrated nitric acid (HNO_3) to pH <2 and stored at 4 °C prior to laboratory examination. The analyzed parameters included hexavalent chromium [Cr(VI)], total iron (Fe), pH, electrical conductivity (EC), temperature, and total dissolved solids (TDS). Cr(VI) concentrations were determined using UV–Visible spectrophotometry through the diphenylcarbazide method at a wavelength of 540 nm, while Fe concentrations were analyzed using atomic absorption spectrophotometry (AAS). Physicochemical parameters were measured in situ using portable multiparameter instruments. Analytical quality assurance procedures included calibration using certified reference standards, triplicate sample analysis, blank sample testing, spike recovery assessment, and instrument calibration verification after every ten samples to ensure analytical precision and reliability. The analytical methods, instruments, and detection limits applied in this study are summarized in Table 2.

Spatial analysis and contamination mapping

Spatial analysis was performed using QGIS version 3.34 to evaluate the spatial distribution of groundwater contamination and plume migration surrounding the Tamangapa landfill. The spatial database integrated several thematic layers, including landfill boundary polygons, administrative boundaries, groundwater sampling locations, settlement distribution, road networks, and population density data. Buffer analysis was conducted to classify contamination risk zones into three categories: a 1 km buffer zone representing the high-risk area, a 1–4 km zone representing moderate contamination risk, and a >4 km zone representing background or reference conditions. Continuous concentration surfaces for Cr(VI) and Fe were generated using the inverse distance weighting (IDW) interpolation method, which was selected due to its suitability for moderate sampling density and its assumption that contaminant concentrations decrease with increasing distance from the pollution source. Groundwater flow direction was interpreted using groundwater elevation measurements and regional topographic gradients derived from DEMNAS elevation data. The resulting spatial interpolation and contamination plume distribution maps are presented in Figure 3.

To evaluate interpolation reliability, cross-validation analysis was performed for both Cr(VI) and Fe interpolation models using a leave-one-out cross-validation (LOOCV) approach. Model performance was assessed using root mean square error (RMSE) and mean absolute error (MAE) statistics. The IDW interpolation method was selected after preliminary comparison

Table 2. Analytical methods, instruments, and detection limits for groundwater quality parameters

Parameter	Unit	Analytical method	Instrument	Detection limit
Cr(VI)	mg L^{-1}	Diphenylcarbazide spectrophotometric method	UV–Vis spectrophotometer (Shimadzu UV-1800)	0.005 mg L^{-1}
Fe	mg L^{-1}	Atomic absorption spectrophotometry (AAS)	PerkinElmer AAnalyst 800	0.01 mg L^{-1}
pH	-	Electrometric method	Hanna HI9813-6 Portable Meter	0.01
Electrical conductivity (EC)	µS cm^{-1}	Conductivity measurement	Portable EC Meter	1 µS cm^{-1}
Temperature	°C	Direct field measurement	Portable multiparameter meter	0.1 °C
Total dissolved solids (TDS)	mg L^{-1}	Derived from EC measurement	Portable multiparameter meter	1 mg L^{-1}

Note: All analytical procedures followed APHA Standard Methods and ISO/IEC 17025 laboratory quality assurance protocols.

with ordinary kriging because the relatively sparse and uneven sampling distribution did not satisfy variogram stability requirements necessary for robust kriging implementation. IDW was therefore considered more appropriate for preserving local concentration gradients and minimizing excessive spatial smoothing under limited sampling density conditions. The power parameter for IDW interpolation was set to 2 based on iterative sensitivity testing, which provided the lowest prediction error and the most stable spatial representation of contamination patterns. Nevertheless, the resulting interpolation surfaces should be interpreted as indicative spatial trends rather than precise contamination boundaries, particularly in areas located far from monitoring wells where interpolation uncertainty increases substantially.

Because the spatial interpolation results were generated from a moderate-density monitoring network, the resulting contamination plume maps should be interpreted as indicative representations of spatial contamination tendencies rather than exact hydrogeological boundaries. The IDW interpolation method was selected to provide practical spatial approximation under limited sampling density conditions; however, additional monitoring wells and repeated temporal observations would improve plume delineation accuracy and reduce uncertainty associated with localized groundwater heterogeneity.

Statistical analysis

Descriptive statistical analysis

All statistical analyses were performed using R software version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistical analysis was applied to characterize groundwater quality and contamination variability surrounding the Tamangapa landfill. The evaluated statistical parameters included mean, median, standard deviation (SD), coefficient of variation (CV), minimum value, and maximum value for each physicochemical and heavy metal parameter. The coefficient of variation was used to assess the degree of spatial heterogeneity in contaminant distribution, where higher CV values indicated stronger variability and potential localized contamination influence. Prior to further statistical evaluation, data normality was examined using the Shapiro–Wilk normality test with a significance level of $p < 0.05$ to determine whether the datasets followed a normal distribution.

Principal component analysis (PCA)

PCA was applied to identify the dominant hydrogeochemical factors controlling groundwater contamination patterns around the Tamangapa landfill. The PCA dataset included Cr(VI) concentration, Fe concentration, distance from landfill, groundwater depth, pH, electrical conductivity (EC), and population density. Only monitoring

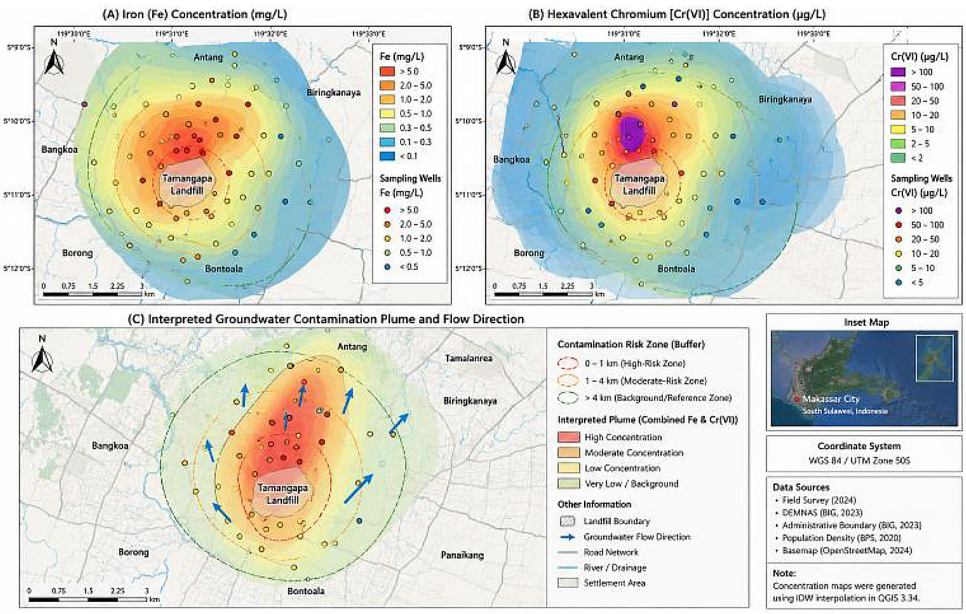

Figure 3. Spatial interpolation of Fe and Cr(VI) concentrations and interpreted groundwater contamination plume around the Tamangapa landfill

wells containing complete datasets for all selected variables were included in the PCA computation to maintain internal consistency within the multivariate analysis. Prior to analysis, all variables were standardized using z-score normalization to eliminate differences in measurement scales and improve comparability among parameters. Principal components with eigenvalues greater than 1 were retained following the Kaiser criterion, while Varimax rotation was applied to enhance factor interpretability and reduce cross-loading among variables. Component loadings greater than 0.60 were considered significant and used for factor interpretation. The PCA results were subsequently interpreted to distinguish contamination sources, hydrogeochemical controls, and anthropogenic influences affecting groundwater quality in the study area. The PCA loading matrix and percentage of explained variance are presented in Table 3.

Because PCA sensitivity may increase when applied to relatively limited sample sizes, the interpretation of component structure in this study was focused primarily on identifying broad hydrogeochemical associations rather than establishing definitive causal mechanisms. The PCA results were therefore interpreted together with spatial distribution patterns, hydrochemical characteristics, and groundwater flow conditions to improve analytical reliability and minimize overinterpretation of multivariate statistical outputs.

The suitability of the dataset for PCA application was evaluated using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. Variables included in the PCA were standardized using z-score normalization prior to analysis. Because several variables were derived from partially overlapping datasets with different analytical coverage, PCA interpretation was limited to identifying broad covariance structures and exploratory hydrochemical associations rather than establishing definitive contamination mechanisms. In addition, scree plot evaluation was performed to support component retention alongside the Kaiser eigenvalue criterion.

Correlation analysis

Spearman's rank correlation analysis was performed to evaluate the relationships among groundwater contamination parameters and environmental variables surrounding the Tamangapa landfill. The analysis examined the associations between heavy metal concentrations [Cr(VI) and Fe], distance from landfill, groundwater depth, pH, electrical conductivity (EC), and population density to identify potential contamination controls and transport mechanisms. Spearman's correlation was selected because several variables did not follow a normal distribution based on the Shapiro–Wilk test results. Positive and negative correlation coefficients were interpreted to determine the strength and direction of monotonic relationships among variables, particularly the influence of landfill proximity and hydrogeochemical conditions on contaminant distribution. The statistical significance level for all correlations was established at $p < 0.05$.

Table 3. Principal component analysis (PCA) loadings and explained variance for groundwater contamination variables

Parameter	PC1 (leachate influence)	PC2 (hydrogeochemical control)	PC3 (anthropogenic influence)	Communality
Cr(VI) concentration	0.82	0.15	0.12	0.71
Fe concentration	0.76	0.45	0.08	0.78
Distance from landfill	−0.79	−0.21	−0.18	0.70
Groundwater depth	0.12	0.81	0.09	0.68
pH	−0.28	−0.73	0.15	0.64
Electrical conductivity (EC)	0.68	0.22	0.25	0.58
Population density	0.08	0.12	0.84	0.73
PCA Summary	PC1	PC2	PC3	
Eigenvalue	3.04	1.69	0.83	
Variance explained (%)	43.4	24.2	11.9	
Cumulative variance (%)	43.4	67.6	78.4	

Note: Loadings > 0.60 are considered significant and are shown in bold.

Human health risk assessment

Human health risk assessment was conducted following the United States Environmental Protection Agency (USEPA) methodology to evaluate both non-carcinogenic and carcinogenic risks associated with groundwater consumption around the Tamangapa landfill. Chronic daily intake (CDI) through groundwater ingestion was calculated using Equation 1:

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

where: *C* represents contaminant concentration (mg L^{-1}), *IR* is ingestion rate (L day^{-1}), *EF* is exposure frequency (days $year^{-1}$), *ED* is exposure duration (years), *BW* is body weight (kg), and *AT* is averaging time (days).

Separate exposure scenarios were evaluated for adults and children to account for differences in water intake rates, body weight, and exposure duration. The risk assessment focused primarily on exposure through groundwater ingestion because local communities rely extensively on shallow groundwater wells for domestic water supply.

For deterministic risk assessment, contaminant exposure concentrations (C) used in chronic daily intake (CDI) calculations were represented by the arithmetic mean concentrations measured within each spatial exposure zone (0–1 km, 1–4 km, and >4 km). Separate concentration datasets were applied for Cr(VI) and Fe according to the corresponding groundwater monitoring results. For conservative exposure evaluation, maximum observed concentrations were additionally considered during uncertainty simulations to evaluate potential worst-case exposure scenarios. Groundwater ingestion was assumed to represent the dominant exposure pathway because local residents primarily rely on shallow groundwater wells for drinking and domestic purposes.

Monte Carlo simulation was subsequently performed to quantify uncertainty and variability associated with human health risk estimates. Probability distributions assigned to input parameters were selected based on environmental exposure literature and observed dataset characteristics. Contaminant concentrations were modeled using lognormal distributions, while ingestion rate and body weight were represented using normal distributions. Exposure duration was treated as a triangular distribution to reflect plausible variability among exposed populations. A total of 10.000 iterations were conducted using @Risk simulation software integrated with Microsoft Excel. Sensitivity analysis was additionally performed using Spearman rank-order correlation coefficients to identify the dominant variables controlling HI variability. Non-carcinogenic risk was estimated using the HQ, calculated as:

$$HQ = \frac{CDI}{RfD} \quad (2)$$

where: *RfD* is the contaminant-specific reference dose.

The cumulative non-carcinogenic risk from multiple contaminants was expressed as the hazard index (HI), calculated using $HI = \Sigma HQ_i$, with HI values greater than 1 indicating potential adverse health effects. Carcinogenic risk (CR) for Cr(VI) exposure was estimated using:

$$CR = CDI \times SF \quad (3)$$

where: *SF* is the cancer slope factor.

The acceptable carcinogenic risk range followed USEPA guidelines of $10^{-6} – 10^{-4}$. The exposure parameters and toxicological reference values used in this study are summarized in Table 4.

Population exposure assessment

Population exposure assessment was conducted by overlaying groundwater contamination zones with village-level population density data obtained from the Indonesian Central Statistics Agency (BPS). The analysis aimed to estimate the spatial distribution of potentially exposed populations surrounding the Tamangapa landfill based on contamination severity and settlement concentration. An exposure index (EI) was calculated using the equation:

$$EI = Population\ Density \times W_c \quad (4)$$

where: W_c represents the contamination weighting factor assigned according to contamination intensity.

Weighting factors were categorized as 1 for low contamination, 2 for moderate contamination, and 3 for high contamination zones. The resulting exposure index was used to identify priority risk areas where high contamination levels overlapped with densely populated settlements. The spatial distribution of exposed populations and contamination risk classifications surrounding the landfill are illustrated in Figure 4.

Uncertainty analysis

Uncertainty analysis was conducted using Monte Carlo simulation to evaluate the variability and confidence associated with groundwater-related human health risks. The simulation incorporated probabilistic distributions for major exposure variables, including contaminant concentration, ingestion rate, exposure duration, and body weight. Contaminant concentrations for Cr(VI) and Fe were represented using lognormal distributions because groundwater contamination data exhibited positive skewness typical of environmental datasets. Ingestion rate and body weight were modeled using normal distributions, while exposure duration was represented using triangular distributions to account for variability in long-term residential exposure scenarios.

A total of 10.000 simulation iterations were performed separately for adult and child exposure groups. Output parameters included mean HQ, HI, CR, 95% confidence intervals, exceedance probabilities for HI > 1, and probability distributions of

Table 4. Exposure parameters and toxicological reference values used for human health risk assessment

Parameter	Adults	Children	Unit	Reference
Ingestion rate (IR)	2.0	1.0	L day⁻¹	USEPA
Exposure frequency (EF)	350	350	days year⁻¹	USEPA
Exposure duration (ED)	30	6	years	USEPA
Body weight (BW)	70	15	kg	USEPA
Averaging time (AT) – non-carcinogenic	ED × 365	ED × 365	days	USEPA
Averaging time (AT) – carcinogenic	25,550	25,550	days	USEPA
Reference dose (RfD) Cr(VI)	0.003	0.003	mg kg⁻¹ day⁻¹	USEPA IRIS
Reference dose (RfD) Fe	0.7	0.7	mg kg⁻¹ day⁻¹	USEPA IRIS
Cancer slope factor (SF) Cr(VI)	0.5	0.5	(mg kg⁻¹ day⁻¹)⁻¹	USEPA

Note: USEPA – United States Environmental Protection Agency; IRIS – Integrated Risk Information System.

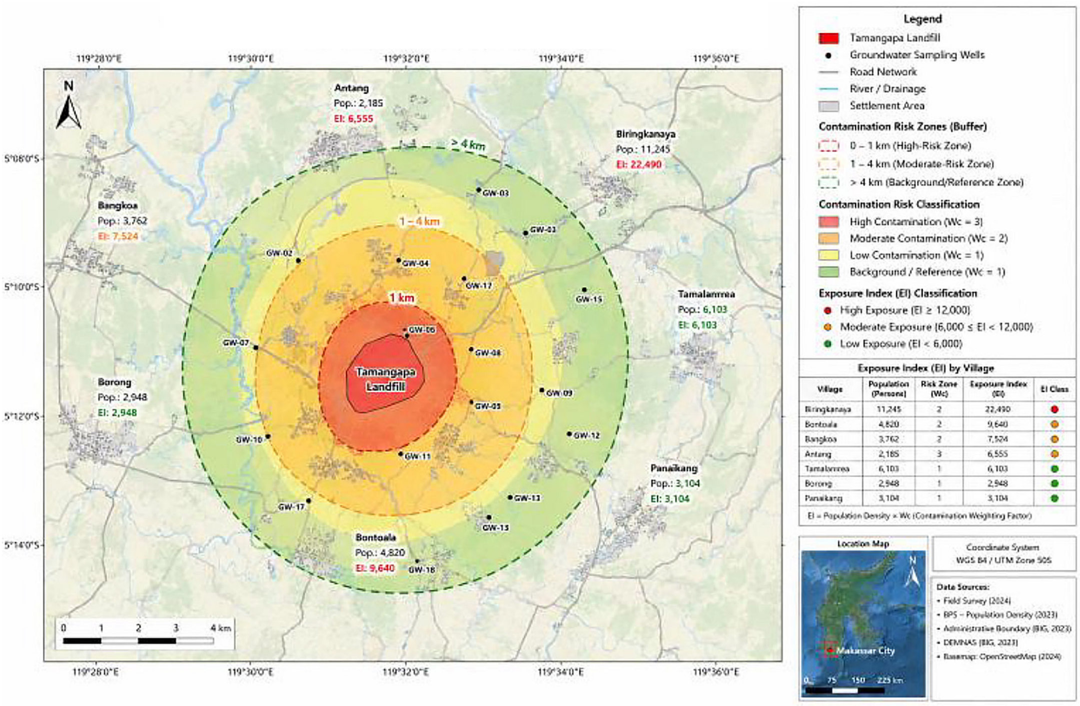

Figure 4. Population exposure zones and contamination risk classification surrounding the Tamangapa landfill

carcinogenic risk exceeding the USEPA acceptable range (10^{-6}–10^{-4}). Sensitivity analysis was conducted using Spearman rank-order correlation coefficients to evaluate the relative influence of input variables on final risk estimates.

The uncertainty analysis indicated that contaminant concentration represented the most influential variable controlling overall exposure risk, followed by ingestion rate and body weight. Simulation outputs further demonstrated that approximately 92% of simulated child exposure scenarios within the 1 km zone exceeded the non-carcinogenic risk threshold (HI > 1), while approximately 65% exceeded the upper acceptable carcinogenic risk threshold for Cr(VI). These results indicate a high probability of adverse health impacts under current groundwater consumption conditions, although uncertainty remains associated with temporal variability and limited sampling density.

Interpolation uncertainty analysis

Spatial interpolation uncertainty was evaluated to assess the reliability of contamination plume delineation generated using the IDW method. Leave-one-out cross-validation (LOOCV) was applied by sequentially removing individual monitoring wells and comparing predicted concentrations with observed values. For Fe interpolation, the model produced an RMSE of 0.42 mg L^{-1} and MAE of 0.31 mg L^{-1}, while Cr(VI) interpolation resulted in an RMSE of 0.018 mg L^{-1} and MAE of 0.012 mg L^{-1}. These error values indicate moderate predictive performance considering the heterogeneous hydrogeological conditions and relatively limited sampling density.

Ordinary kriging was initially evaluated as an alternative interpolation method. However, unstable semivariogram structures and insufficient spatial autocorrelation caused unreliable kriging performance, particularly for Cr(VI) data characterized by sparse sampling coverage. Consequently, IDW interpolation was retained because it provided more stable and interpretable spatial outputs under the existing dataset conditions. Similar methodological considerations have been reported in previous landfill contamination studies where moderate sampling density constrained the applicability of geostatistical interpolation techniques.

Despite the acceptable interpolation performance, uncertainty increases in peripheral areas located far from monitoring wells. Therefore, the interpreted contamination plume extending approximately 4 km downgradient should be considered an estimated contamination tendency rather than an exact contamination boundary. Additional monitoring wells and multi-season sampling campaigns would improve spatial confidence and enable more robust plume delineation in future studies.

Quality assurance and ethical considerations

All laboratory analyses and sample handling procedures followed ISO/IEC 17025 quality assurance standards to ensure analytical accuracy, consistency, and reliability. Instrument calibration was conducted using certified reference materials, while analytical precision and recovery efficiency were evaluated through duplicate sample analysis, blank sample testing, and spike recovery procedures. Quality control verification was performed routinely throughout the analytical process to minimize measurement uncertainty and contamination bias. In addition, all secondary health-related data used in this study were anonymized and aggregated at the community level to maintain confidentiality and ethical compliance. The overall study protocol, including environmental sampling and data management procedures, was reviewed and approved by the Hasanuddin University Research Ethics Committee.

RESULTS AND DISCUSSION

Groundwater quality characteristics: Distribution of heavy metals and physicochemical parameters

Groundwater quality analysis revealed significant variations in heavy metal concentrations and physicochemical characteristics surrounding the Tamangapa landfill. Chromium [Cr(VI)] concentrations ranged from below the analytical detection limit to 0.12 mg L^{-1}, while Fe concentrations varied between 0.15 and 4.64 mg L^{-1}. The highest concentrations of both metals were predominantly identified in monitoring wells located north of the landfill, coinciding with the interpreted regional groundwater flow direction. Acidic groundwater conditions were also observed in several wells, with pH values ranging from 5.4 to

7.1. Elevated electrical conductivity (EC) values indicated increased dissolved ion concentrations likely associated with landfill leachate infiltration. The descriptive statistical summary of groundwater quality parameters is presented in Table 5.

The high exceedance rate of Fe indicates that iron contamination represents the dominant groundwater quality issue in the study area. Approximately 80.8% of monitored wells exceeded the Indonesian drinking water standard of 0.30 mg L^{-1}, suggesting extensive metal mobilization in the shallow aquifer system. Chromium contamination was less spatially extensive but exhibited localized concentrations exceeding the permissible limit by more than twofold. Similar groundwater contamination patterns associated with landfill leachate migration have been reported in India, Iraq, and tropical urban landfill systems, where elevated Fe, Cr, EC, and acidic groundwater conditions were closely linked to uncontrolled leachate infiltration and shallow aquifer vulnerability (Mishra et al., 2019; Hammash and Abed, 2022; Gupta et al., 2024). The relatively high coefficients of variation observed for both Cr(VI) and Fe indicate heterogeneous contaminant distribution and support the hypothesis that groundwater contamination is strongly influenced by localized leachate infiltration pathways rather than uniform geogenic background conditions. Comparable spatial heterogeneity and plume irregularity were also documented by Alao et al. (2023) and Alao et al. (2024), who demonstrated that seasonal leachate migration and preferential subsurface pathways strongly influence contaminant distribution in landfill-affected aquifers.

The elevated Fe concentrations may be associated with reductive dissolution processes under low-oxygen conditions generated by organic-rich landfill leachate. Similar findings have been reported in tropical landfill environments where anaerobic degradation enhances dissolved metal mobility and increases groundwater contamination potential (Lindamulla et al., 2022; Abdel-Shafy et al., 2024). In addition, acidic pH conditions observed in several wells likely contributed to increased solubility and transport of dissolved iron, consistent with observations reported by Abiriga et al. (2021) and Alao (2025), who identified low-pH reducing environments as important controls on landfill plume migration. The elevated EC and TDS values recorded in this study further support the influence of dissolved inorganic and organic constituents derived from landfill leachate, which have been widely recognized as major indicators of groundwater deterioration around open dumping sites (Gupta et al., 2024; Rajan et al., 2024). Similar contamination behavior has also been documented in Indonesian landfill systems, including the Tamangapa landfill itself and the Cadika landfill in South Sulawesi, where hydrochemical anomalies and contaminant migration were strongly controlled by tropical climatic conditions, shallow groundwater tables, and inadequate leachate containment infrastructure (Artiningsih et al., 2019; Alimuddin et al., 2026).

Spatial distribution of groundwater contamination

Spatial interpolation analysis using the IDW method demonstrated that groundwater contamination was highly concentrated in the northern sector of the landfill area. Figure 5 illustrates the interpreted groundwater contamination plume based on Cr(VI) and Fe concentrations. The spatial distribution pattern revealed three major contamination zones. The first zone consisted of a high-risk area within a 1 km radius north of the landfill where Cr(VI) concentrations reached 0.12 mg L^{-1} and Fe concentrations exceeded 2.8 mg L^{-1}. The second zone extended between 1 and 4 km from the landfill and was characterized by moderate contamination levels dominated

Table 5. Descriptive statistics of groundwater quality parameters around Tamangapa landfill

Parameter	N	Mean	Median	SD	Minimum	Maximum	Drinking water standard	% Exceedance
Cr(VI) (mg L^{-1})	10	0.047	0.032	0.038	<0.005	0.12	0.05	40%
Fe (mg L^{-1})	26	1.28	0.85	1.21	0.15	4.64	0.30	80.8%
pH	36	6.2	6.3	0.4	5.4	7.1	6.5–8.5	33%
EC (µS cm^{-1})	36	425	380	210	120	890	–	–
TDS (mg L^{-1})	36	285	240	145	80	610	500	18%

primarily by elevated Fe concentrations. Beyond 4 km, groundwater quality generally complied with drinking water standards, although isolated hotspots remained detectable. Similar downgradient contamination patterns have been reported in landfill-affected aquifers in India, Iraq, and Sub-Saharan Africa, where heavy metal concentrations decreased progressively with distance from landfill boundaries due to dilution, sorption, and geochemical attenuation processes (Mishra et al., 2019; Hammash and Abed, 2022; Abiriga et al., 2021). Alao et al. (2023) and Alao et al. (2024) also demonstrated that landfill leachate plumes commonly exhibit heterogeneous spatial distributions controlled by hydrogeological heterogeneity, seasonal recharge, and preferential contaminant pathways. In tropical countries, elevated rainfall intensity and shallow groundwater systems have been recognized as major drivers accelerating contaminant dispersion and plume elongation (Lindamulla et al., 2022; Gupta et al., 2024).

Although the highest Cr(VI) concentrations were concentrated predominantly within the first 1 km downgradient zone, detectable Cr(VI) contamination signals remained observable at lower concentrations up to approximately 2 km from the landfill boundary.

The interpreted contamination plume orientation strongly followed the regional groundwater flow direction derived from topographic gradients and groundwater elevation data. Minimal contamination was detected in southern and western sectors, indicating that contaminant transport was anisotropic rather than radially uniform. These findings provide strong evidence that the landfill acts as the primary contamination source and that plume migration is controlled by hydrogeological conditions. Comparable anisotropic plume migration behavior has been documented in previous landfill studies using geochemical and geophysical approaches, where contaminant transport preferentially followed hydraulic gradients and permeable alluvial sediments rather than exhibiting isotropic diffusion (Alao, 2025; Alao et al., 2023). Similar hydrogeological controls were also identified in Indonesian landfill environments by Artiningsih et al. (2019) and Alimuddin et al. (2026), who reported that contaminant migration around tropical landfill systems was strongly influenced by shallow aquifer characteristics and groundwater flow direction. Furthermore, climate-driven increases in infiltration and groundwater recharge may further intensify plume mobility under future environmental change scenarios (Brand and Spencer, 2024; Lekshmy and Achari, 2026).

Importantly, the interpolated contamination plume appeared to extend considerably beyond the commonly applied 1 km regulatory monitoring buffer used in Indonesia. Cross-validation analysis indicated moderate interpolation

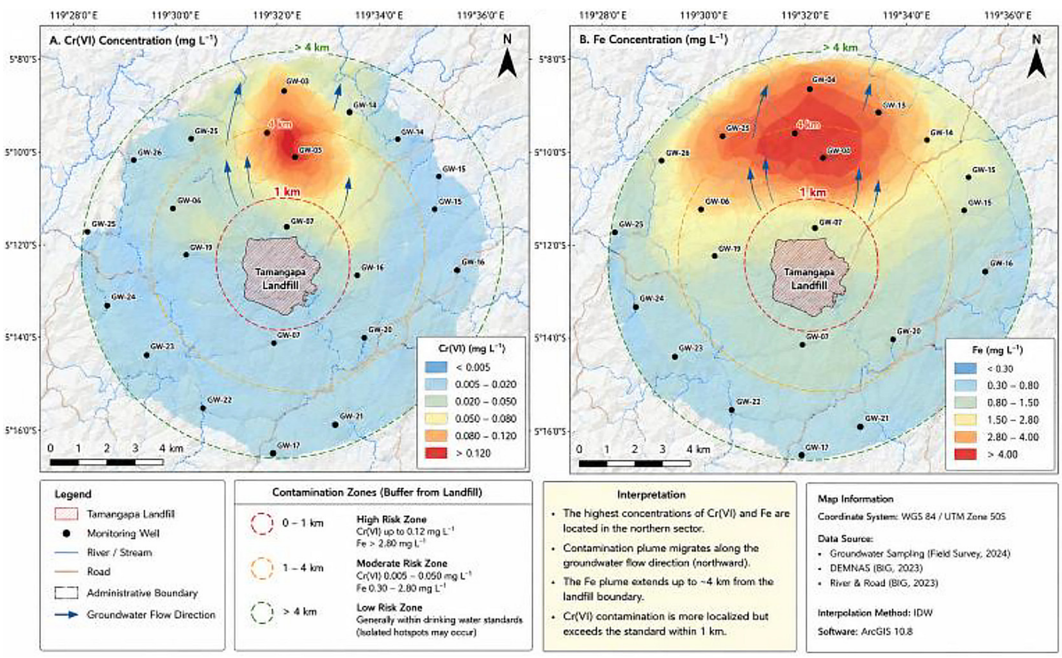

Figure 5. Spatial interpolation of Cr(VI) and Fe concentrations showing groundwater contamination plume migration surrounding Tamangapa landfill

reliability; however, the estimated plume boundary should be interpreted cautiously because uncertainty increases in areas with lower monitoring well density. The observed Fe plume tendency reached approximately 4 km downgradient from the landfill boundary, suggesting that current monitoring regulations may underestimate contamination migration potential in tropical alluvial aquifer systems. The observed Fe plume reached approximately 4 km downgradient from the landfill boundary, suggesting that current monitoring regulations substantially underestimate contamination migration potential in tropical alluvial aquifer systems. Similar concerns regarding inadequate landfill monitoring buffers and underestimation of groundwater contamination risks have been highlighted globally, particularly in humid developing regions where landfill infrastructure remains poorly engineered (Gupta et al., 2024; Rajan et al., 2024). Roy et al. (2025) further demonstrated that persistent contaminants originating from historic landfill plumes may migrate over large distances and continue impacting groundwater and surface water ecosystems for decades. The extended contamination radius identified in this study therefore supports the argument that fixed-distance buffer regulations are inadequate for humid tropical landfill environments characterized by high recharge rates, shallow groundwater tables, and permeable unconsolidated sediments.

Principal component analysis (PCA)

PCA was applied as an exploratory multivariate statistical tool to identify major covariance patterns among groundwater quality variables surrounding the landfill. The PCA results are presented in Table 6. Three principal components with eigenvalues greater than 1 were retained following the Kaiser criterion, collectively explaining 78.4% of the total dataset variance. Prior to PCA application, sampling adequacy and variable suitability were evaluated using the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity. The overall KMO value was 0.64, indicating acceptable sampling adequacy for exploratory PCA application, while Bartlett's test was statistically significant ($p < 0.001$), confirming sufficient inter-variable correlation structure for multivariate analysis.

The first principal component (PC1) explained 43.4% of total variance and exhibited strong positive loadings for Cr(VI), Fe, and EC, combined with a strong negative loading for distance from the landfill. Rather than representing a definitive contamination mechanism, this component is interpreted as a statistical association consistent with potential landfill-related hydrochemical influence because elevated dissolved ions and heavy metal concentrations were spatially associated with landfill proximity. Similar covariance patterns have been reported in landfill-affected aquifers where contaminant concentrations decrease progressively with increasing distance from waste disposal sites (Mishra et al., 2019; Alao et al., 2023).

The second principal component (PC2) explained 24.2% of total variance and was characterized primarily by groundwater depth and pH. This component may reflect hydrogeochemical conditions influencing contaminant mobility within the shallow aquifer system, particularly the potential influence of acidic and reducing

Table 6. Principal component analysis (PCA) loadings and explained variance

Variable	PC1	PC2	PC3	Communality
Cr(VI)	0.82	0.15	0.12	0.71
Fe	0.76	0.45	0.08	0.78
Distance from landfill	-0.79	-0.21	-0.18	0.70
Groundwater depth	0.12	0.81	0.09	0.68
pH	-0.28	-0.73	0.15	0.64
EC	0.68	0.22	0.25	0.58
Population density	0.08	0.12	0.84	0.73
Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)	
PC1	3.04	43.4	43.4	
PC2	1.69	24.2	67.6	
PC3	0.83	11.9	78.4	

environments on dissolved metal behavior. However, because PCA identifies statistical covariance rather than direct geochemical processes, the interpretation of PC2 should be considered inferential rather than definitive. Comparable statistical associations between pH, groundwater depth, and dissolved metal concentrations have been documented in landfill-contaminated aquifers where redox-sensitive hydrochemical conditions influence contaminant persistence and transport (Hammash and Abed, 2022; Abdel-Shafy et al., 2024).

The third principal component (PC3) explained 11.9% of total variance and was primarily associated with population density. This component may indicate the presence of secondary anthropogenic influences unrelated directly to landfill leachate, such as domestic wastewater inputs or urban surface activities. Nevertheless, because the explained variance of PC3 was comparatively low, its interpretation remains tentative and should not be considered conclusive evidence of specific contamination sources. Overall, the cumulative variance explained by the three retained components suggests that the selected variables adequately captured the dominant statistical variability within the groundwater quality dataset.

The scree plot analysis supported retention of the first three principal components, as eigenvalues declined substantially after PC3 and approached the inflection point characteristic of diminishing explained variance contributions (Figure S1, Supplementary Material). Figure S1. Scree plot showing eigenvalue distribution and retained principal components for groundwater contamination variables. The first three principal components exhibited eigenvalues greater than 1 and were therefore retained following the Kaiser criterion.

Correlation between hydrochemical variables

Spearman correlation analysis revealed statistically significant relationships between contaminant concentrations and hydrogeochemical parameters. The correlation matrix is presented in Table 7. Cr(VI) exhibited a strong negative correlation with distance from the landfill (ρ = -0.78), confirming that landfill proximity is the dominant factor controlling chromium contamination. Iron also showed a significant negative relationship with distance, although the correlation was weaker than that observed for Cr(VI). This suggests that Fe remains mobile over longer transport distances due to favorable reducing conditions within the aquifer. Similar inverse relationships between heavy metal concentrations and distance from landfill boundaries have been widely reported in contaminated aquifer systems, where contaminant attenuation occurs progressively along groundwater flow paths (Mishra et al., 2019; Alao et al., 2023). Alao et al. (2024) further demonstrated that seasonal leachate migration can maintain elevated Fe concentrations at greater downgradient distances due to prolonged reducing conditions in shallow groundwater systems. Comparable findings were also observed in tropical landfill environments where metal contamination plumes extended beyond conventional monitoring zones because of high recharge rates and permeable alluvial sediments (Lindamulla et al., 2022; Gupta et al., 2024).

Electrical conductivity displayed strong positive correlations with both Cr(VI) and Fe concentrations, indicating that EC can serve as a useful indirect indicator of leachate contamination. The negative correlation between Fe and pH further supports the role of acidic conditions in enhancing dissolved iron mobility. Similar hydrochemical relationships have been documented in previous

Table 7. Spearman correlation matrix of groundwater contamination variables

Parameter	Cr(VI)	Fe	Distance	Depth	pH	EC
Cr(VI)	1.00	0.62*	-0.78**	0.15	-0.32	0.71**
Fe	0.62*	1.00	-0.58*	0.22	-0.48*	0.52*
Distance	-0.78**	-0.58*	1.00	0.08	0.25	-0.63**
Depth	0.15	0.22	0.08	1.00	-0.35	0.12
pH	-0.32	-0.48*	0.25	-0.35	1.00	-0.28
EC	0.71**	0.52*	-0.63**	0.12	-0.28	1.00

Note: *Significant at $p < 0.05$; **Significant at $p < 0.01$.

landfill studies where elevated EC reflected increased dissolved ionic constituents originating from landfill leachate infiltration (Abdel-Shafy et al., 2024; Hammash and Abed, 2022). The association between acidic pH and enhanced Fe mobility also agrees with observations by Alao (2025), who emphasized that low-pH and reducing environments significantly increase heavy metal dissolution and groundwater contamination risks. Moreover, Abiriga et al. (2021) demonstrated that landfill leachate intrusion frequently alters aquifer geochemistry by increasing ionic strength and promoting metal transport under confined groundwater conditions. Overall, the correlation analysis confirms that contaminant transport is strongly associated with leachate migration processes and hydrogeochemical conditions, consistent with recent global assessments of landfill-related groundwater degradation in urban environments (Rajan et al., 2024; Roy et al., 2025).

Human health risk assessment

Non-carcinogenic risk

Human health risk assessment revealed significant non-carcinogenic risks associated with groundwater consumption, particularly for children living near the landfill. HQ and HI values are summarized in Table 8. Children living within the 1 km contamination zone exhibited Hazard Index values exceeding the acceptable threshold (HI > 1), indicating potential adverse health effects associated with chronic groundwater consumption. The higher risks observed in children are attributable to lower body weight and higher water intake relative to body mass. Adult exposure risks remained below the critical threshold but approached unacceptable levels in high-contamination areas. Similar findings have been reported in previous landfill-related groundwater studies where children consistently exhibited higher non-carcinogenic risks than adults due to greater exposure sensitivity and intake-to-body-weight ratios (Alao et al., 2023; Rajan et al., 2024). Majee et al. (2026) also observed elevated health risks among children living near municipal waste disposal facilities in tropical urban settlements, particularly under conditions of shallow groundwater dependence. Furthermore, Gupta et al. (2024) emphasized that chronic exposure to landfill-derived heavy metals through groundwater ingestion can significantly increase long-term public health risks in densely populated urban areas. The elevated HI values identified in the present study therefore indicate that vulnerable populations residing near the Tamangapa landfill may face substantial exposure risks if untreated groundwater continues to be used for domestic purposes.

Monte Carlo uncertainty analysis supported the deterministic risk assessment results and demonstrated substantial probability of non-carcinogenic exposure risks among children residing near the landfill. The probabilistic simulation indicated that 92% of child exposure scenarios within the 1 km contamination zone exceeded the acceptable Hazard Index threshold (HI > 1). The mean simulated HI value for children within this zone was 2.14, with a 95% confidence interval ranging from 1.32 to 3.41. In contrast, only 18% of adult exposure simulations exceeded the acceptable risk threshold, indicating comparatively lower vulnerability among adult populations.

Sensitivity analysis revealed that contaminant concentration was the dominant contributor to HI variability, accounting for approximately 61% of total model sensitivity, followed by ingestion rate (23%) and body weight (11%). These findings indicate that uncertainty in groundwater contaminant concentrations exerts the strongest influence on overall exposure risk estimation.

The results also demonstrated clear risk attenuation with increasing distance from the landfill. Beyond 4 km, both adult and child exposure risks declined to acceptable levels. These findings indicate that groundwater contamination poses localized but significant public health concerns in communities located downgradient of the landfill. Comparable spatial risk gradients have been documented in previous studies where contaminant concentrations and associated health risks decreased progressively away from landfill boundaries due to dilution, dispersion, and natural attenuation processes (Mishra et al., 2019; Abiriga et al., 2021). Alao (2025) further reported that hydrogeological conditions strongly influence the spatial extent of groundwater-related health risks in landfill environments, particularly in permeable shallow aquifers. Similar conclusions were also reported by Hammash and Abed (2022), who found that populations located within close proximity to landfill sites experienced substantially greater exposure risks compared with distant communities. Collectively, these findings reinforce the importance of expanding groundwater

Table 8. Hazard quotient (HQ) and hazard index (HI) for groundwater exposure

Exposure zone	Population group	HQ Cr(VI)	HQ Fe	HI	Risk category
0–1 km	Adults	0.85	0.12	0.97	Moderate
0–1 km	Children	1.82	0.25	2.07	High
1–4 km	Adults	0.32	0.08	0.40	Low
1–4 km	Children	0.68	0.17	0.85	Moderate
>4 km	Adults	0.08	0.03	0.11	Acceptable
>4 km	Children	0.17	0.06	0.23	Acceptable

monitoring and implementing targeted public health interventions in high-risk zones surrounding tropical landfill systems.

Carcinogenic risk of Cr(VI)

Carcinogenic risk assessment for Cr(VI) indicated elevated lifetime cancer risks for exposed populations, particularly within the high-contamination zone. Figure 6 illustrates the spatial distribution of carcinogenic risk surrounding the landfill.

Probabilistic carcinogenic risk analysis further demonstrated elevated uncertainty-adjusted cancer risks within the high-exposure zone. Monte Carlo simulation results indicated that approximately 65% of child exposure scenarios within the 1 km zone exceeded the USEPA upper acceptable carcinogenic risk threshold of 10^{-4}. The median carcinogenic risk value for children was estimated at 1.8×10^{-4}, while the 95th percentile reached 3.4×10^{-4}. Adult carcinogenic risks remained comparatively lower but still exceeded acceptable thresholds in several simulation iterations. These findings suggest that long-term groundwater consumption may represent a substantial chronic health concern for vulnerable populations residing near the landfill.

The estimated carcinogenic risk for children within the 1 km zone exceeded the upper acceptable USEPA threshold of 10^{-4}, indicating a potentially significant public health concern. Moderate carcinogenic risks persisted within the 1–4 km contamination plume, suggesting that long-term exposure to untreated groundwater may increase cancer risk among exposed communities. Similar carcinogenic risk patterns associated with landfill-derived heavy metal contamination have been reported in previous groundwater studies conducted in rapidly urbanizing regions (Mishra et al., 2019; Alao et al., 2023). Rajan et al. (2024) highlighted that chronic exposure to carcinogenic contaminants in groundwater represents one of the most critical environmental health challenges in developing urban settlements, particularly where groundwater remains a primary domestic water source. Comparable findings were also reported by Majee et al. (2026), who identified elevated cancer risks in populations residing near municipal solid waste disposal facilities affected by persistent heavy metal contamination. In addition, Alao (2025) emphasized that landfill leachate migration in shallow aquifer systems can sustain long-term carcinogenic exposure pathways, especially under conditions of inadequate containment infrastructure and high groundwater vulnerability. The persistence of carcinogenic risks within the 1–4 km plume in the present study further supports observations by Roy et al. (2025), who demonstrated that contaminant plumes originating from historic landfills may extend considerable distances downgradient and continue exposing surrounding ecosystems and communities over extended periods. Table 9 shows the Monte Carlo simulation outputs for non-carcinogenic and carcinogenic risk assessment. These findings reinforce the need for alternative drinking water sources, stricter groundwater protection policies, and enhanced monitoring programs in tropical megacities experiencing rapid urban growth and increasing landfill pressure.

Population exposure assessment

Population exposure analysis demonstrated that approximately 15,000 residents are located within the interpreted groundwater contamination plume extending northward from the landfill. Figure 7 presents the spatial overlap between contamination zones and population density distribution.

The highest exposure intensity was concentrated within the 1 km high-risk zone, where approximately 2.800 residents rely on shallow groundwater resources for domestic use.

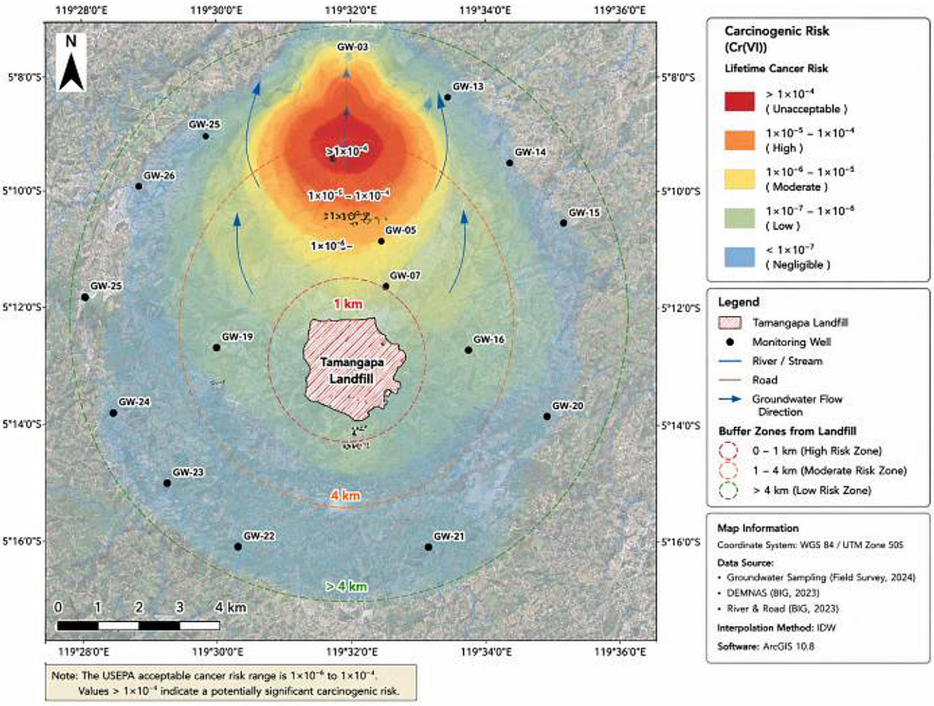

Figure 6. Spatial distribution of carcinogenic risk associated with Cr(VI) exposure from groundwater consumption

Table 9. Monte Carlo simulation outputs for non-carcinogenic and carcinogenic risk assessment

Exposure zone	Population group	Mean HI	95% CI	Probability HI > 1 (%)	Mean CR	Probability CR > 10^{-4} (%)
0–1 km	Adults	0.98	0.62–1.45	18	6.8×10^{-5}	12
0–1 km	Children	2.14	1.32–3.41	92	1.8×10^{-4}	65
1–4 km	Adults	0.43	0.22–0.71	4	2.4×10^{-5}	3
1–4 km	Children	0.88	0.54–1.42	36	7.6×10^{-5}	18
>4 km	Adults	0.12	0.05–0.21	<1	3.1×10^{-6}	<1
>4 km	Children	0.24	0.10–0.38	2	6.7×10^{-6}	<1

Moderate exposure conditions were identified within the 1–4 km zone, which accommodates approximately 12,200 residents. Although contamination levels were lower in this zone, the larger exposed population resulted in a substantial cumulative exposure burden.

The exposure index analysis demonstrated that moderate-risk zones contributed most significantly to overall population exposure due to their larger population density. This finding highlights the importance of integrating both contamination severity and population distribution into environmental risk management strategies. Similar observations were reported by Alao et al. (2025), who demonstrated that communities located along downgradient landfill plume pathways experienced disproportionately higher cumulative exposure risks despite moderate contaminant concentrations. Majee et al. (2026) also observed that densely populated urban settlements surrounding tropical landfills exhibited elevated long-term health vulnerability because large populations depended on untreated shallow groundwater resources. In Indonesia, Artiningsih et al. (2019) identified contamination risks associated with landfill-derived mercury migration around the Tamangapa landfill, indicating that vulnerable residential communities are directly influenced by contaminant dispersion from waste disposal sites. Comparable spatial exposure patterns have been documented in other tropical landfill systems where rapid urban expansion and inadequate groundwater protection infrastructure intensified public exposure to leachate-derived

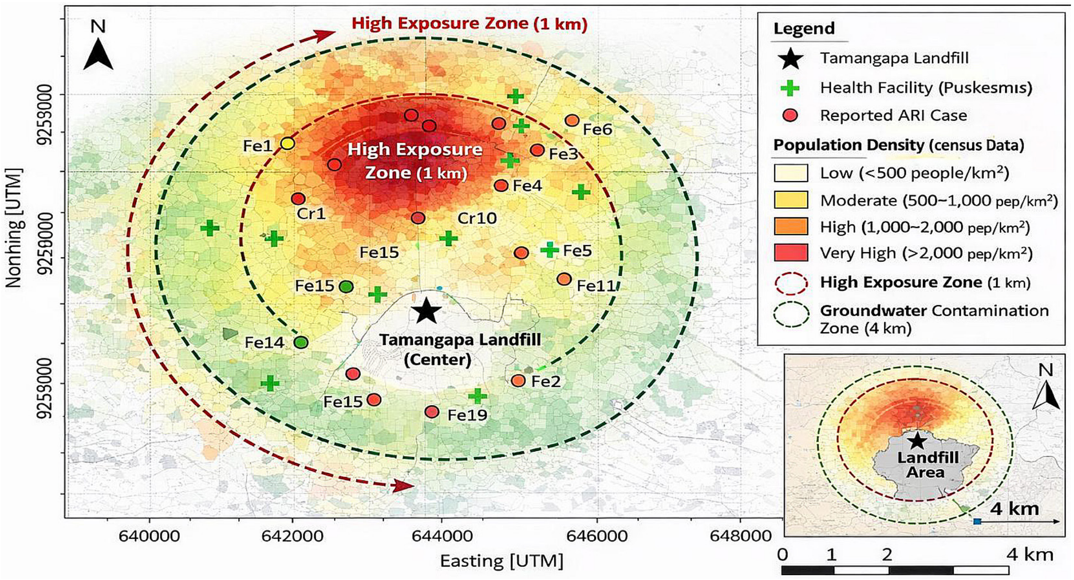

Figure 7. Population exposure zones and contamination risk classification surrounding Tamangapa landfill

contaminants (Mishra et al., 2019; Gupta et al., 2024). The observed exposure distribution also supports the broader argument proposed by Rajan et al. (2024) that hydrogeochemical contamination assessments should incorporate demographic vulnerability and population density to accurately characterize groundwater-related public health risks. Furthermore, Alao (2025) emphasized that the interaction between landfill plume migration, shallow aquifer systems, and urban population growth represents a critical environmental health challenge in developing tropical megacities, particularly where groundwater remains the primary domestic water source.

Integrated interpretation of tropical landfill contamination

The observed contamination patterns reflect the interaction between tropical climatic conditions, hydrogeological vulnerability, and prolonged open-dumping practices. High annual rainfall exceeding 2.500 mm likely enhances leachate generation and vertical infiltration into the shallow aquifer system. Simultaneously, high organic waste content promotes reducing conditions that facilitate iron mobilization and persistent groundwater contamination.

Compared with several landfill studies conducted in temperate environments, the Tamangapa contamination plume appeared to exhibit relatively longer downgradient migration distances, particularly for Fe contamination. While many temperate landfill investigations reported plume attenuation within approximately 0.5–1 km from landfill boundaries, the present study identified Fe contamination tendencies extending up to approximately 4 km downgradient under tropical hydrogeological conditions. Nevertheless, direct quantitative comparison between studies should be interpreted cautiously because plume behavior is strongly influenced by multiple site-specific factors, including aquifer permeability, groundwater recharge, landfill engineering systems, waste composition, and monitoring density. Therefore, the present findings suggest a potential tendency for enhanced contaminant mobility under humid tropical conditions rather than definitive evidence of universally larger plume dimensions in tropical landfill systems.

The persistence of Cr(VI) contamination within the first kilometer indicates rapid contaminant transport before complete reduction to Cr(III). Meanwhile, the greater mobility of Fe reflects sustained reducing conditions within the aquifer system. The combined hydrogeochemical and spatial evidence confirms that landfill leachate remains the dominant contamination source affecting groundwater quality around the Tamangapa landfill.

Nevertheless, the interpreted contamination extent should be considered an approximation influenced by sampling density, interpolation assumptions, and temporal variability in groundwater conditions. The IDW interpolation method provides a practical representation of contaminant distribution under moderate sampling coverage; however, additional monitoring wells and multi-seasonal observations would improve plume delineation accuracy and reduce spatial uncertainty. Consequently, the present findings are intended to provide a scientifically informed risk-screening framework rather than an exact prediction of contaminant transport boundaries.

Nevertheless, caution is required when interpreting plume persistence and long-distance contaminant transport because the present study was based on a single hydrological monitoring period. Temporal variability associated with seasonal recharge, rainfall intensity, and fluctuating groundwater levels was not directly evaluated in the current investigation. Therefore, the interpreted contamination plume represents prevailing contamination conditions during the sampling period rather than a definitive long-term contaminant transport model. Future multi-season investigations integrating groundwater flow modeling and temporal monitoring are necessary to improve understanding of plume evolution under tropical climatic conditions.

Implications for groundwater management and environmental policy

The findings of this study have important implications for landfill management and groundwater protection policies in tropical developing cities. First, the observed contamination plume demonstrates that conventional 1 km monitoring buffers are inadequate for humid tropical landfill environments. Expanded monitoring networks extending at least 4 km downgradient are necessary to accurately capture contamination migration. To synthesize the integrated findings of this study into a practical environmental management framework, the Source–Pathway–Receptor–Impact–Mitigation (SPRIM) concept was applied. The framework integrates hydrogeochemical contamination sources, contaminant transport pathways, exposed populations, environmental and health impacts, and potential mitigation strategies into a unified conceptual model relevant for tropical landfill systems. The SPRIM framework provides a structured synthesis of our findings (Figure 8).

Second, the high exposure risks identified for children emphasize the urgent need for alternative water supply programs in affected communities. The installation of engineered liners, leachate collection systems, and groundwater interception infrastructure should be prioritized to reduce contaminant migration. In addition, continuous groundwater quality monitoring should incorporate hydrochemical indicators such as EC and pH alongside heavy metal parameters.

Finally, the integrated hydrogeochemical and spatial assessment framework applied in this study provides a practical approach for environmental risk assessment in tropical megacities where monitoring resources are often limited. The combination of multivariate statistics, spatial interpolation, and health risk assessment enables more comprehensive evaluation of landfill-induced groundwater contamination and supports evidence-based environmental governance.

Figure 8 presents the SPRIM framework application to the Tamangapa landfill, integrating source characteristics, pathway mechanisms, receptor populations, quantified impacts, and mitigation options derived from hydrogeochemical and spatial risk assessment. The source (S) is characterized by waste input of 600–800 tons/day with 60–65% organic content, leachate containing elevated heavy metals such as Cd (0.08 mg/L), Pb (0.11 mg/L), and Fe (5.8 mg/L) exceeding regulatory standards, as well as significant gas emissions with CH_4 reaching 10.46 Gg/year in 2020 and increasing by 143% during the COVID-19 period, under continued open dumping conditions and overcapacity since 2019. The pathway (P) analysis indicates northward groundwater flow driven by a hydraulic gradient of 0.008, with contaminant transport distances reaching up to 4 km for Fe and 2 km for Cr(VI), moderated by attenuation processes including dilution, sorption, and redox reactions, and facilitated by preferential flow through alluvial sand and gravel with high hydraulic conductivity. The receptor (R) includes approximately 15,000 people within a 4 km northern exposure zone, with vulnerable groups such as children experiencing higher exposure and scavengers facing direct contact risks, alongside affected ecosystems including groundwater-dependent wetlands and agricultural wells, as well as two primary healthcare facilities (Puskesmas) located within the exposure zone. The impact (I) assessment reveals significant environmental and health consequences, including 80.8% exceedance of Fe and 40% exceedance of Cr(VI) in water quality measurements, health risk indices exceeding 1 for children within a 1 km radius, carcinogenic risk values reaching up to 3×10^{-4}, annual

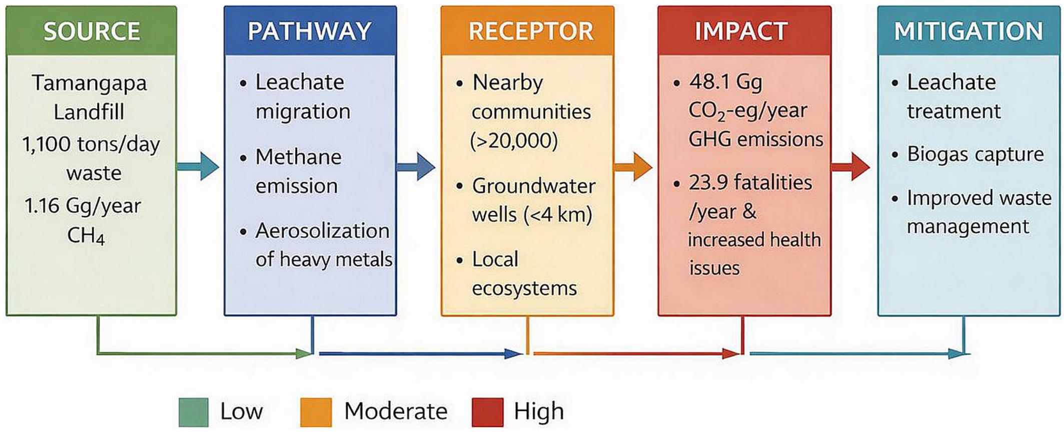

Figure 8. SPRIM framework application to Tamangapa landfill

acute respiratory infection (ARI) treatment costs exceeding IDR 248 million, and notable social implications involving livelihood dependence of 500–700 informal workers on landfill activities. Finally, the mitigation (M) strategies encompass engineering interventions such as liner installation, leachate treatment systems, and planned gas capture through a waste-to-energy facility (PLTSa) targeted for 2027, biological approaches including bioremediation potential using six identified indigenous microbial isolates, regulatory measures such as expanding buffer zones to at least 4 km and strengthening environmental monitoring, and social interventions aimed at providing alternative livelihood programs for informal workers.

STUDY LIMITATIONS

Several limitations should be considered when interpreting the findings of this study. In addition, the spatial distribution of Cr(VI) was evaluated using a relatively limited number of monitoring wells due to analytical and logistical constraints, which may reduce interpolation precision for localized contamination hotspots. First, groundwater sampling was conducted during a single hydrological period and therefore may not fully represent seasonal variations in contaminant transport and aquifer recharge processes. Second, the number of monitoring wells available for Cr(VI) analysis was relatively limited compared with the overall spatial extent of the study area, potentially affecting interpolation precision and multivariate statistical robustness. Third, the spatial interpolation maps generated using the IDW method represent estimated concentration surfaces based on available sampling points and may not fully capture small-scale hydrogeological heterogeneity. In addition, the health risk assessment applied deterministic exposure assumptions derived from USEPA guidelines and therefore may not completely reflect local behavioral variability and individual exposure differences. Despite these limitations, the study provides important baseline evidence regarding landfill-induced groundwater contamination under tropical hydrogeological conditions and offers a practical framework for preliminary environmental risk assessment in data-limited developing urban regions. Future studies should incorporate larger multi-season datasets, groundwater flow modeling, geochemical speciation analysis, and long-term monitoring to improve contamination prediction accuracy and strengthen causal interpretation.

Several limitations should be acknowledged in interpreting the spatial contamination results. First, the monitoring well density remains relatively limited for high-resolution plume delineation across heterogeneous tropical aquifer systems. Second, the interpolation outputs are influenced by spatial sampling distribution and may contain increased uncertainty in peripheral areas lacking monitoring wells. Third, the study relied on single-season groundwater observations, which may not fully capture temporal variations associated with seasonal recharge dynamics. Consequently, the contamination plume maps presented in this study should be interpreted as indicative representations of contamination trends rather than exact hydrogeological boundaries. Future investigations incorporating denser monitoring networks, multi-season sampling, and geostatistical uncertainty modeling are recommended to improve plume characterization accuracy.

Although probabilistic uncertainty analysis improved exposure characterization, several limitations remain. The simulation outputs are influenced by assumptions regarding exposure parameter distributions and are constrained by the relatively limited groundwater monitoring dataset. Temporal variability associated with seasonal groundwater recharge was not fully incorporated into the current probabilistic framework. Consequently, the risk estimates presented in this study should be interpreted as probabilistic approximations of potential exposure conditions rather than precise epidemiological predictions.

Although the observed contamination plume in the present study appeared relatively extensive compared with several previously reported landfill investigations, the study did not perform a formal comparative meta-analysis between tropical and temperate landfill systems. Consequently, the results should not be interpreted as universal evidence that tropical landfill plumes are consistently larger than temperate plumes. Differences in hydrogeological conditions, waste composition, engineered containment systems, monitoring density, and analytical methods among studies may substantially influence reported plume dimensions and contaminant transport behavior.

CONCLUSIONS

This study presents an integrated hydrogeochemical and spatial risk assessment of groundwater contamination surrounding the Tamangapa landfill using combined hydrochemical analysis, GIS-based spatial interpolation, multivariate statistics, and human health risk assessment. The results indicate that landfill leachate is the dominant factor influencing groundwater quality deterioration in the downgradient aquifer system. However, because the study was based on a moderate-density monitoring network and single-season sampling, the interpreted contamination plume should be considered a spatial risk-screening representation rather than a definitive long-term hydrogeological characterization.

Differential contaminant mobility analysis reveals contrasting behaviors, where Cr(VI) exhibits rapid attenuation with a half-distance of 0.82 km due to reductive processes, while Fe demonstrates persistent mobility with a half-distance of 2.48 km under reducing conditions. Health risk assessment indicates severe exposure impacts, with Monte Carlo simulation indicated that approximately 92% of simulated child exposure scenarios within the 1 km high-exposure zone exceeded the acceptable non-carcinogenic risk threshold (HI > 1) and 65% exceeding acceptable carcinogenic risk thresholds (CR > 10^{-4}), affecting an estimated 15,000 residents within a 4 km radius. The study suggests that humid tropical hydrogeological conditions, combined with shallow unconfined aquifers and prolonged open-dumping practices, may contribute to relatively broader contaminant migration compared with several previously reported temperate landfill systems. However, these comparisons should be interpreted cautiously because plume dimensions are strongly influenced by site-specific hydrogeological characteristics, landfill engineering conditions, and monitoring approaches.

Policy recommendations include immediate provision of alternative water supplies for 2.800 residents within the 1 km zone and installation of leachate collection systems, short-term expansion of the buffer zone to at least 4 km alongside strengthened groundwater monitoring, and long-term transition toward sanitary landfill systems, landfill gas utilization, and alternative livelihood development for informal workers. Theoretically, the study demonstrates the applicability of integrated SPRIM and PCA-based frameworks in tropical developing-country contexts, provides empirical evidence of tropical amplification in landfill contamination, and challenges uniform regulatory buffer approaches by supporting site-specific, risk-based management strategies. In the context of global waste generation projected to reach 3.88 billion tonnes by 2050, this study offers a replicable integrated methodology combining hydrogeochemical characterization, multivariate statistics, spatial analysis, and health risk assessment to support evidence-based environmental management in data-scarce settings.

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