
NON-PARAMETRIC ASSESSMENT OF WIND-SECTOR AND ELEVATION EFFECTS ON CONTAMINANT DISTRIBUTION AROUND A CEMENT FACTORY

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Contaminants released from industrial point sources can build up in air, soil and water surrounding the source. A non-parametric statistical framework was used to assess the spatial distribution of contamination indicators for particulate matter (PM; $n = 9$), soil ($n = 17$), and water ($n = 52$) around a cement factory. Most variables, especially in the soil and water, were significantly non-normally distributed as indicated by Shapiro-Wilk tests ($p < 0.05$) consistent with point-source deposition. Simple radial distance was insignificant ($p > 0.05$) for all matrices under the Spearman's rank correlation analysis, suggesting that radial distance alone is not a good predictor of contamination gradients. Stratifying by prevailing upwind/downwind sector greatly increased the correlations, particularly those for particulate deposition rate and weight ($\rho = -1.000$, though based on a downwind subset of only $n = 5$ and therefore statistically fragile) and between topsoil lead and potassium ($\rho = -0.800$, also not formally significant at this smaller sample size); correlations remained low for water ($\rho = -0.05$ to -0.29) suggesting the soil column would act as a buffer to prevent vertical migration. The contamination of the topsoil was mostly independent of elevation, suggesting a depositional source from the atmosphere, while cadmium in the paired elevation subset of the water dataset ($n = 30$ of the 52 water points) was nominally negatively correlated with elevation ($\rho = -0.3057$; uncorrected $p = 0.049$, not surviving a multiple-comparisons correction), suggesting that the Cd is accumulating in low-lying hydrological sinks driven by topography. Our results demonstrate that the use of directional and topographic sampling designs substantially improves gradient resolution over radial distance sampling designs, with relevance to environmental monitoring around point-source facilities.

Keywords: Industrial point sources; Spearman's rank correlation; wind-sector stratification; water contamination; cement industry

1. INTRODUCTION

Point sources of air-borne particulate matter (PM) and associated trace metals emitted from cement manufacturing and other heavy industrial activities have been identified and are deposited onto adjacent soils, where the metals may leach into shallow ground water. The situation in Nigeria is exemplified by the studies conducted directly around cement manufacturing facilities, where topsoil levels of cadmium, cobalt, chromium, lead and nickel were found to be higher in proximity to the plant, and electrical conductivity and some metal concentrations lower, than away from the plant (Akpambang *et al.*, 2022). Similar distance-decay relationships are reported from other cement plants, in some of which additional information indicates that the decay is not exclusively radial; Bermudez *et al.* (2010) have reported that the concentrations of lithogenic material and metals in the topsoil around a cement plant in Argentina were best related by the combination of distance from the plant and topsoil organic matter content, with maximum enrichment on the downwind side of the plant under the prevailing wind direction. Likewise, Parlak *et al.* (2023) intentionally sampled soils from cement-plant sites at different angles and distances (1-7 km) since the authors anticipated that concentrations of heavy metals would differ with distance as well as sector and this was indeed the case.

The results are directionally sensitive, because atmospheric dispersion from a stack is not a diffuse or non-point source; the footprints of pollution are elongated and asymmetric, with the contamination's direction and shape determined in large part by the local meteorology (especially the wind direction and speed). Outside the cement industry, it is a documented trend that the soil heavy metal and magnetic susceptibility signatures around abandoned steel and iron plants have the highest values in the sector associated with the prevailing wind directions of the plant (Yang *et al.*, 2020). Despite this, there remains a significant amount of environmental monitoring data, which still uses a straight distance from the facility as the main explanatory variable for contaminant decline, which has the potential to mask real spatial gradients when samples are collected both upwind (background) and downwind (impacted) of a facility and analyzed at the same distance.

A second layer of complexity is specific to groundwater and is the topography. Classical hydrogeological theory dictates that water will flow from high potential to low potential; that regional or horizontal groundwater flow and solutes will be controlled primarily by topography and geology, and not horizontal distance from a contamination source (Freeze & Cherry, 1979). This topographic control is particularly affecting mobile, weakly sorbing contaminants such as cadmium, which is highly mobile across a wide range of near neutral pH conditions, compared to other regulated heavy metals like lead or chromium which are more readily immobilized by the sorption to soil and aquifer material (Kubier *et al.*, 2019). Due to being also a carcinogen at chronic low-level exposure and the establishment of WHO drinking-water guideline value of 0.003 mg/L (World Health Organization, 2017), cadmium behavior is of special practical and scientific interest. By contrast, contamination to soil is primarily due to fallout from the atmosphere, and is likely to be more evenly distributed across elevation than is water contamination. These processes (directional, wind-driven, and vertical, elevation-driven) must be separated from the simple horizontal distance to properly identify the contamination pathways and to be able to design a monitoring network that is statistically able to detect a real effect.

This study seeks to fill that gap by implementing a three tier, non-parametric, statistical framework for particulate matter, soil and water data taken around a cement manufacturing plant. Due to the skewed distribution of environmental contamination data near point sources (a few samples may contain much higher concentrations than the majority), throughout non-parametric methods were used because they are well suited for testing monotonic relationships, which is the equivalent of the Pearson correlation in the context of order statistics (Spearman, 1904). Specifically, the study was designed to: (1) characterize the distributional properties of each measured parameter using the Shapiro-Wilk test to determine the class of inferential statistics to be used; (2) test whether levels of contaminants decrease predictably with simple radial distance from the factory; (3) test whether stratification by prevailing downwind sector of samples would reveal more interpretable spatial gradients than would the undirected distance model; and (4) evaluate whether the elevation of sampling points has an independent effect on contaminant distribution, particularly in water. These objectives test the hypothesis that contamination gradients around a point-source industrial facility can only be described by combining directional and topographic controls, and that a distance alone is not sufficient.

2. METHODOLOGY

2.1 Study Area

The study was carried out around a Cement Plant which is situated in Obajana, Kogi State, North-Central Nigeria between latitude 7°54'N to 7°56'N and longitude 6°24'E to 6°27'E with an elevation of 200 - 420m (Global Energy Monitor, 2025). The Plant is the biggest single site cement plant in Africa, which utilizes a nearby quarry estimated to have 647 million tonnes of limestone reserves (Dangote Cement Plc, 2026). The land uses of the surrounding area comprise Guinea savannah vegetation, smallholder farm land, rural settlements, partially surrounded by quarry and plant infrastructure (Musa & Kpanache, 2014). The region is situated in the tropical wet and dry climatic zone of Kogi State and has an average annual rainfall of 1,839 mm, average temperatures in the region range between 27 and 31 °C (Akpambang *et al.*, 2022). The two-part regional wind rose classification in this study is based on dry season with the influence of harmattan (a dry dusty north easterly trade wind blowing from over the Sahara desert) and wet season with the influence of

monsoonal wind originating from the Atlantic (moist southwesterly monsoonal wind). Geologically, Kogi State overlies both Precambrian Basement Complex to the west and Cretaceous – Recent sedimentary cover (Anambra Basin) to the east while Obajana lies on top of a good thick limestone formation with lateritic residual soils overlying it, which is also mined locally as a cement additive (Obaje, 2018). Shallow ground water occurs in the weathered/fractured basement aquifer or sedimentary aquifer which is common in the area and is tapped locally by hand dug wells and boreholes (Akpambang *et al.*, 2022). The sampling locations for this study were distributed from the plant stack ranging from 0-5km, both in the dominant downwind direction and also upwind and across wind for directional stratification. Figure 1 is a schematic illustration of this design and does not depict actual GPS-derived sampling coordinates or true inter-point spacing.

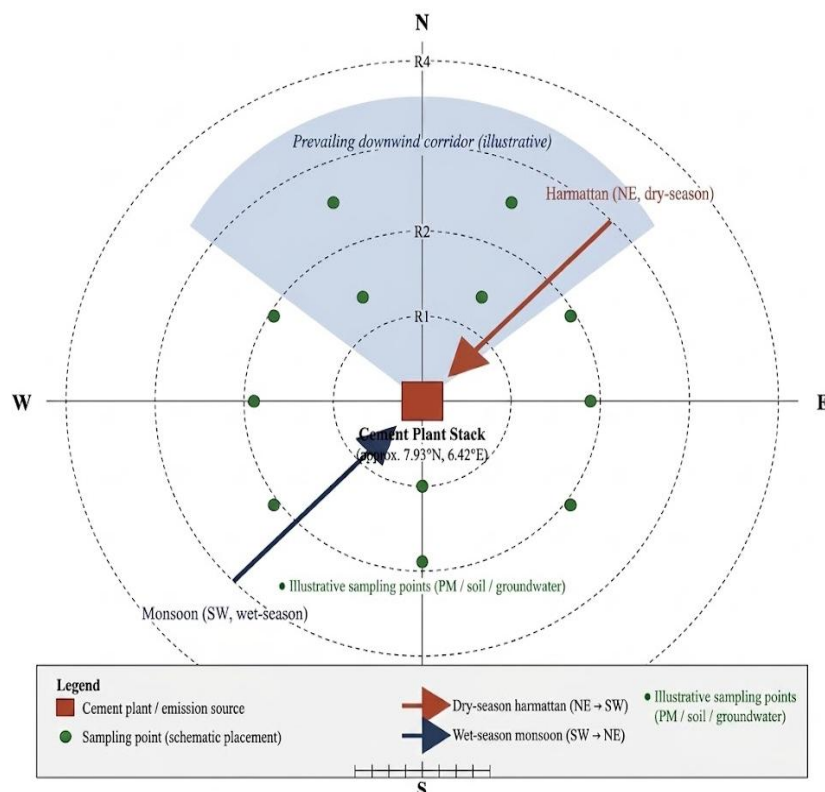


Figure 1: Schematic Site Layout and Wind Regime of the Study Area

2.2 Sampling Design and Sample Size

Three sample sets were collected: particulate matter deposition samples ($n = 9$), soil samples ($n = 17$), and water samples ($n = 52$; a subset of $n = 30$ water points with paired elevation data was used for the elevation-correlation analysis in Section 3.4). Sampling followed a radial (spoke-and-ring) design, in which points were distributed along transects radiating from the factory stack at the eight principal compass directions (N, NE, E, SE, S, SW, W, NW) and crossed with four concentric distance rings spanning the 1–5 km impact zone: R1 (≈ 1.0 km), R2 (≈ 2.0 km), R3 (≈ 3.5 km), and R4 (≈ 5.0 km, serving as the far-field/background reference). Not every direction $\times$ ring combination was sampled in every matrix, given the differing sample sizes across PM, soil, and water; point allocation was instead weighted toward the prevailing downwind corridor to maximize power for the directional analysis in Section 3.3, consistent with the sampling logic used in comparable cement-plant studies (Parlak *et al.*, 2023). A sampling point was classified as falling within the prevailing downwind sector if its bearing from the stack fell within a $\pm 45^\circ$ arc centered on the seasonal-mean wind vector for the sampling period, determined from the nearest long-term meteorological record; the Nigerian Meteorological Agency (NiMet) synoptic station serving the Lokoja/Kogi area, cross-checked against ERA5 reanalysis wind fields for the same period (Hersbach *et al.*, 2020; Nigerian Meteorological Agency, n.d.); with all remaining points classified as upwind/crosswind. Sampling was conducted during the peak dry season (harmattan period, February 2025), when the region's wind

direction is most stable and unimodal; this seasonal window is consistent with the strong, stable downwind correlations reported in Section 3.3. The resulting downwind vs. upwind/crosswind split was $n = 5$ vs. $n = 4$ for particulate matter, $n = 10$ vs. $n = 7$ for soil, and $n = 30$ vs. $n = 22$ for water; these stratified subset sizes, particularly for PM, are small and the resulting downwind correlations should be interpreted with this in mind (see Sections 3.3.1 and 3.3.4). Note that the water downwind subset ($n = 30$) is distinct from the elevation-paired subset (also $n = 30$; Section 3.4) — the two are defined by different criteria (wind sector vs. availability of elevation data) and do not necessarily contain the same sampling points.

2.3 Laboratory Analysis

Particulate matter weight and deposition rate were determined using passive dustfall collectors (petri-dish method) and analyzed gravimetrically. Soil physicochemical parameters (pH, electrical conductivity) and elemental concentrations (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Pb^{2+} , Mn, Cd, Cr, Ni, SO_4^{2-} , PO_4^{3-} , Cl⁻, P) were determined following ASTM D6044 guidelines (ASTM, 2002). Water samples were analyzed for physical indicators (pH, electrical conductivity, turbidity, total dissolved solids, total suspended solids, total hardness, total alkalinity, free chlorine), major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl⁻, SO_4^{2-} , HCO_3^- , CO_3^{2-} , PO_4^{3-}), and trace/heavy metals (Pb^{2+} , Cd, Cr, Ni, Cu, Zn, Mn, Hg, As, Fe, F⁻, NO_3^-) using APHA Standard Methods (APHA, 2017). Sampling-point elevation (m) was recorded using handheld GPS. Comprehensive QA/QC protocols were implemented to ensure analytical accuracy, precision, and reproducibility in accordance with established standard methods (APHA, 2017). Field and reagent blanks were employed to detect potential contamination during sampling and laboratory procedures. Instrument calibration was conducted using certified reference standards, with calibration curves achieving correlation coefficients ($R^2 \geq 0.995$). Recovery efficiency was assessed through spike-recovery tests, yielding acceptable recoveries within 85–115%, while analytical precision was evaluated using duplicate samples ($\geq 10\%$ of total samples), maintaining relative percent differences below 10%. Accuracy was further verified using standard reference materials. For hydrochemical analyses, ionic balance error (IBE) was computed and maintained within $\pm 5\%$, confirming the reliability of major ion determinations (APHA, 2017). Method detection limits for trace metals were established prior to analysis, and all reported concentrations exceeded these thresholds.

2.4 Statistical Analysis

Data normality was tested for each measured variable in each matrix (PM, soil and water) by Shapiro Wilk test (Shapiro & Wilk, 1965) with the null hypothesis that the sample was from a normally distributed population which was rejected at $p < 0.05$. The normality assumption was violated in all subsequent bivariate relationships and therefore all of them were examined with the non-parametric Spearman's rank correlation coefficient (ρ) (Spearman, 1904) which is a monotonic association measure for skewed environmental data. For each matrix three correlation analyses were carried out: (i) ρ between the concentration of contaminant and the simple radial distance from the factory stack (not direction); (ii) ρ between the concentration of contaminant and the distance in the prevailing downwind corridor, determined from site wind-rose data; and (iii) ρ between the concentration of contaminant and the elevation of the sampling point (m) (not radial distance). All tests were performed with $\alpha = 0.05$, p values of 0.05 – 0.10 were indicated as marginal/suggestive trends. There are many variables tested within each matrix and thus, results should be interpreted with the potential for false positives, a sensitivity follow-up check, Benjamini & Hochberg (1995) false discovery rate correction, is recommended to be done as a follow-up and is applied directly to the study's single nominally significant result (the cadmium-elevation correlation) in Section 3.4.3 and revisited in the Conclusion. Data analysis was conducted using R v4.3, Python SciPy (Stats module) and SPSS v26.

3. RESULTS AND DISCUSSION

3.1 Distribution Normality (Shapiro-Wilk Test)

In all three matrices, the majority of the measured variables were significantly more deviant from a normal distribution than not, with $p < 0.05$, which meant that non-parametric correlation methods could be used throughout the study.

3.1.1 Particulate Matter

Both PM metrics were highly right-skewed (Table 1), reflecting the typical exponential increase and decrease of concentrations seen in point-source atmospheric deposition.

Table 1: Shapiro-Wilk Normality Test Results for Particulate Matter Variables

Variable	W-statistic	p-value
Weight (g)	0.6722	0.0007
Deposition rate	0.6561	0.0004

Note: $n = 9$. $p < 0.05$ indicates significant deviation from normality.

3.1.2 Soil Samples

The majority of the structural minerals and chemical trace indicators of soil were significantly non-normal; a lesser number of minerals (Mg^{2+} , Na^+ , Pb^{2+} , Mn) were not significantly different from normal (Figure 2).

3.1.3 Water Samples

The majority of physical and chemical properties in the water were not normal, only a few major ions (Na^+ , Cl^- , SO_4^{2-} , PO_4^{3-} , and total solids) were consistent with a normal distribution (Figure 2).

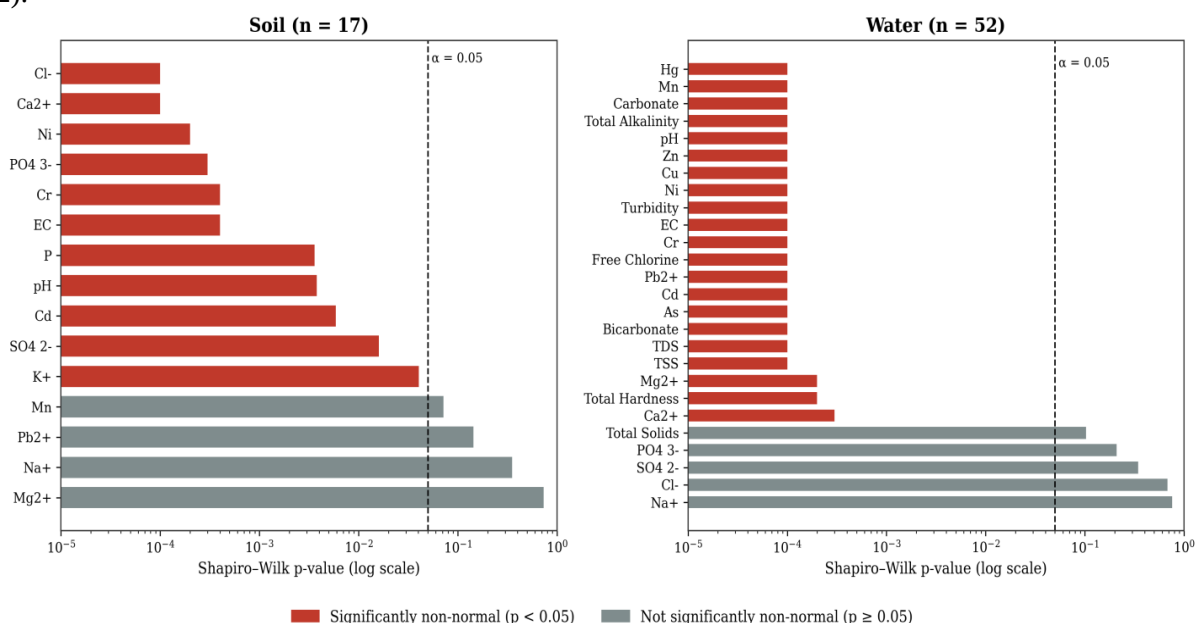


Figure 2: Shapiro-Wilk Normality Test Results for Soil and Water Variables (log-scaled p-value; dashed line marks $\alpha = 0.05$).

Why Distributions were predominantly Non-Normal.

The non-normality seen in all three matrices (Figure 2) is typical of contamination associated with a point source that can lead to a right-skewed distribution. This is not just a function of small sample sizes, as the Shapiro-Wilk procedure was created as a general test for departures from normality because such departures, in particular skewed distributions, are common among real, uncontrolled sampling data (Shapiro and Wilk, 1965), and skewed heavy-metal distributions are

regularly reported around the point source of a cement plant and a metal smelter (Bermudez *et al.*, 2010; Parlak *et al.*, 2023). This pattern should be considered as a methodological signature of the point-source impact, rather than a mere nuisance of the statistical kind that should be transformed away, as a number of near-source samples drive the overall pattern.

3.2 Spearman's Rank Correlation with Radial Distance

Spearman's rank correlation (ρ) was then calculated for each variable vs the factory distance calculated from a stack without any stratification by direction to see if there was a predictable decrease in contamination with distance from the factory.

3.2.1 Particulate Matter ($n = 9$)

Weight and deposition rate were negatively correlated with distance in a monotonic manner (deposition rate $\rho = -0.3333$, $p = 0.381$; weight $\rho = -0.2667$, $p = 0.488$), reflecting the decreased impact of particulates with distance from the stack, but neither was of statistical significance at this sample size (Figure 3).

3.2.2 Soil Samples ($n = 17$)

Several other contaminants from the industrial plume had the expected decreasing relationship with distance (cadmium, manganese, lead, nickel) and pH had the expected increasing relationship ($\rho = +0.3341$) indicating a slight increase in soil pH with distance from the depositional source. The trend for all the univariate analyses was not significant at the $\alpha = 0.05$ level (Table 2).

Table 2: Spearman's Rank Correlation between Soil Parameters and Radial Distance

Parameter	ρ	p-value
pH	+0.3341	0.1900
Cadmium (Cd)	-0.3036	0.2361
Manganese (Mn)	-0.3031	0.2370
Potassium (K ⁺)	-0.2722	0.2905
Phosphorus (P)	-0.2672	0.2999
Lead (Pb ²⁺)	-0.2220	0.3919
Nickel	-0.2211	0.3937
Chromium (Cr)	+0.1585	0.5435
Calcium ion (Ca ²⁺)	-0.1436	0.5825
Sulfate (SO ₄ ²⁻)	+0.1410	0.5893
Sodium (Na ⁺)	-0.1324	0.6126
Magnesium (Mg ²⁺)	+0.1172	0.6541
Electrical Conductivity	-0.0969	0.7115
Chloride (Cl ⁻)	+0.0687	0.7934
Phosphate (PO ₄ ³⁻)	+0.0385	0.8833

3.2.3 Water Samples ($n = 52$)

Magnesium ($\rho = -0.2682$, $p = 0.086$) and cadmium ($\rho = -0.2594$, $p = 0.097$) had a weak negative correlation with distance while other factors were not significant (Table 3).

Table 3: Spearman's Rank Correlation between Water Parameters and Radial Distance

Parameter	ρ	p-value
Magnesium (Mg^{2+})	-0.2682	0.0860
Cadmium (Cd)	-0.2594	0.0972
Turbidity	-0.2356	0.1331
Chloride (Cl^-)	+0.2181	0.1654
Total Dissolved Solids (TDS)	-0.2143	0.1729
Chromium (Cr)	-0.2129	0.1758
Phosphate (PO_4^{3-})	-0.2014	0.2009
Calcium ion (Ca^{2+})	+0.1647	0.2973
Total Suspended Solids (TSS)	+0.1576	0.3190
Total Solids	-0.1557	0.3247
Sulfate (SO_4^{2-})	-0.1264	0.4250
pH	-0.1245	0.4319
Lead (Pb^{2+})	-0.1180	0.4567
Copper (Cu)	-0.1149	0.4686
Total Alkalinity	+0.1153	0.4670
Arsenic (As)	-0.0991	0.5322
Bicarbonate	-0.0900	0.5710
Mercury (Hg)	+0.0768	0.6286
Electrical Conductivity	-0.0490	0.7582
Zinc (Zn)	-0.0427	0.7882
Sodium (Na^+)	+0.0331	0.8353
Nickel	-0.0267	0.8666
Total Hardness	+0.0221	0.8894
Carbonate	-0.0192	0.9039
Manganese (Mn)	-0.0116	0.9420
Free Chlorine	+0.0036	0.9817

3.2.4 Interpretation of the Radial-Distance Model

None of the radial-distance correlations reached significance in any matrix (Tables 2–3; Figure 3), which motivates the wind-stratified analysis in Section 3.3.

Why Simple Radial Distance is an Insufficient Predictor.

There was no statistically significant correlation between contaminant concentration and undirected radial distance, which is in agreement with the physical fact of atmospheric dispersion that contaminant plumes do not deposit in uniform concentric rings around a stack, but rather in elongated and skewed deposition patterns that are oriented along the prevailing wind axis. That's why several of the similar studies explicitly account for wind direction or compass sector from the outset, in addition to distance: Parlak *et al.* (2023) sampled the soils from cement plants in six compass directions at four distances from the sources because they expected there to be variation in soil contamination at the sector level; Yang *et al.* (2020) found that the sectors with the most contaminated soils were directly related to the prevailing wind directions at the site, not the sectors closest to the sources. In the undirected model reported here, background (upwind) samples are combined with impacted (downwind) samples where the impacted samples are at the same radial distance, causing the true spatial gradient to be diluted and capable of being masked. The finding has a direct methodological implication: sampling designs and statistical models which are only based on the Euclidean distance from a point source may systematically underestimate actual contamination gradients, concretely supported by the increase in the correlation coefficients when accounting for direction in Section 3.3.

3.3 Spearman's Rank Correlation Filtered by Wind Direction

The samples were split into the dominant downwind corridor (determined from the site wind rose data) and the correlation analysis was repeated to see if contaminant levels decreased more clearly with distance when direction is controlled for.

3.3.1 Particulate Matter

Both PM parameters showed a perfect negative correlation with distance in the downwind corridor ($\rho = -1.000$; Figure 3), based on a downwind-stratified subset of only $n = 5$ of the 9 total PM sampling points. A perfect rank correlation is close to inevitable with so few points, since almost any small set of values can be placed in a single monotonic order; the associated p-value is also not reliable here, because the standard t-approximation used to test Spearman's ρ has a $(1 - \rho^2)$ term in its denominator that goes to zero as ρ approaches ± 1 , which can report a spuriously small p-value regardless of sample size. This downwind PM result should therefore be read as a suggestive gradient rather than a statistically confirmed one, pending replication with a larger downwind sample.

3.3.2 Soil Samples

Correlation between heavy-industrial indicators and the downwind sector improved significantly, with lead and potassium each having $\rho = -0.800$, cadmium $\rho = -0.400$, and manganese having $\rho = -0.632$, although none were formally significant for this smaller downwind-stratified sample ($n = 10$; Figure 3). The downwind trends were positive for sulfate ($\rho = +0.800$), which suggests additional secondary deposition downwind, and for pH ($\rho = +0.400$), which again showed a positive trend as soils became more neutral/alkaline with distance from the source.

3.3.3 Water Samples

Water correlations were weak and non-significant across the downwind corridor (nickel $\rho = -0.287$; total dissolved solids $\rho = -0.193$; cadmium $\rho = -0.162$; sulfate $\rho = -0.048$; all $p > 0.05$; downwind-stratified $n = 30$; Figure 3), indicating that the soil column may buffer or attenuate vertical transport of contaminants deposited on the surface to the water table.

3.3.4 Summary of Directional Findings

Across the three matrices, downwind stratification produced strong, consistent distance-decay correlations for particulate matter and topsoil metals, but only weak, non-significant correlations for water (Figure 3; interpreted below).

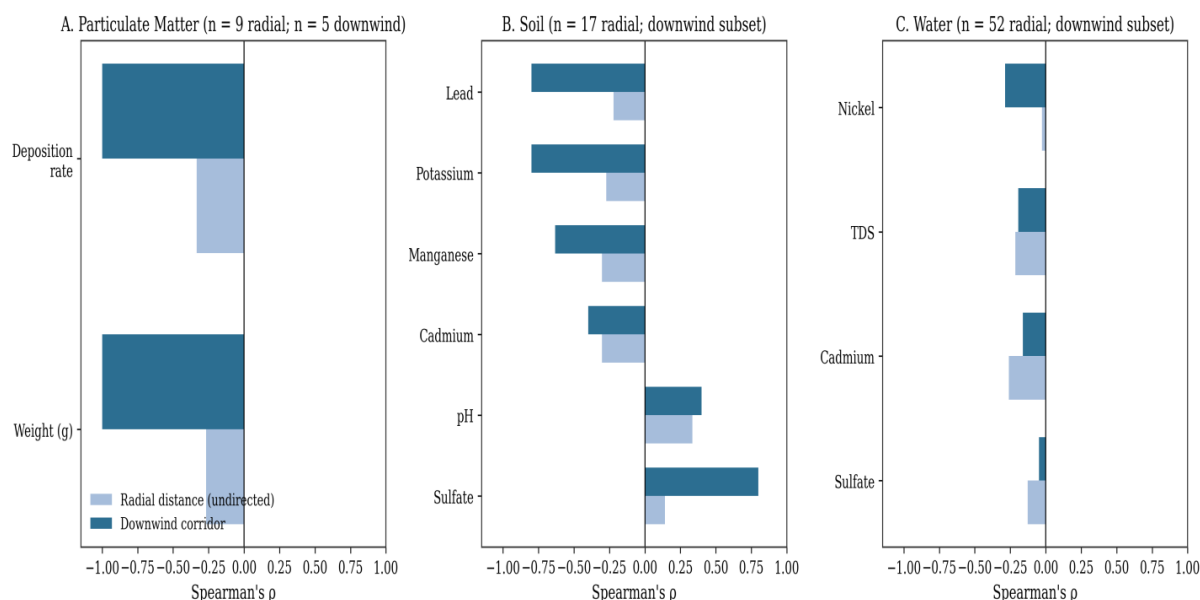


Figure 3: Spearman's ρ under the undirected radial-distance model versus the downwind-corridor model, for PM, soil, and water parameters reported in both analyses (Sections 3.2–3.3).

Directional Stratification substantially strengthens Spatial Signals. Although several of the correlations were not formally significant, due to small sample sizes in the stratified subsets, there was a significant improvement in the correlation with the prevailing downwind corridor (Figure 3) for both particulate matter ($\rho = -1.000$) and topsoil heavy metals (ρ up to -0.800 for lead and potassium).

This pattern was similar to that found by Bermudez *et al.* (2010) who found that the highest topsoil metal concentrations extracted with HCl were found downwind of the cement plant at the site where the wind flow was favorable, and were able to predict heavy metal concentrations with soil distance and soil organic matter once direction was taken into account. The coherence of the direction and magnitude of the present PM and soil results also indicates a coherent pathway from the atmosphere to the soil: material is transported downwind and settles on the surface of the top soil in a spatially decaying pattern that is similar to the one observed in the aerial deposition gradient. For soil and topsoil metals, the direction and magnitude of these trends are a compelling descriptive pattern, though formal confirmation at conventional significance levels would require larger downwind sample sizes. The PM correlation is a separate case: with a downwind subset of only $n = 5$, the perfect $\rho = -1.000$ reported in Section 3.3.1 is statistically fragile rather than confirmatory (see the caveat there). This directional coherence is consistent with the wider literature demonstrating that wind-aware sampling methods reveal gradients that are not observed in distance-only based methods (Parlak *et al.*, 2023; Yang *et al.*, 2020).

Evidence for Soil as a Geochemical Buffer Protecting Water.

However, water correlations were relatively weak and statistically flat (Section 3.3.3) within the same downwind corridor as were PM and soil correlations. This is consistent with the soil column being a geochemical buffer; that is, heavy metals and other contaminants that are added to the surface of the soil are significantly adsorbed, retained or transformed by the soil matrix before they can leach into the underlying aquifer. This interpretation is consistent with the differential mobility behaviour of heavy metals in soil-water systems described in the literature: Cadmium is comparatively weakly sorbed and is expected to be mobile in solution over a wide near neutral pH range, giving it the highest potential to be mobilized in groundwater, whereas more strongly sorbed metals such as lead and chromium are expected to remain strongly bound to soil particles and are therefore not expected to show a significant relationship with topography in groundwater (Kubier *et al.*, 2019). The present finding has a positive practical implication as it indicates that, at least for the present, groundwater at this site may be fairly well protected from surface contamination for most of the metals; however, there is also a negative implication which is that continued or increased deposition could eventually cause the soil to become saturated with metals and therefore the adsorption capacity is no longer available for protection; therefore, a longitudinal monitoring program should be undertaken to monitor this; cadmium is an example metal that is relatively poorly retained and should be monitored particularly.

3.4 Spearman's Rank Correlation with Sampling-Point Elevation

To separate topography-driven (vertical) transport from radial distance or wind sector (horizontal) deposition, Spearman's rank correlation was calculated between each variable and the sampling-point elevation (m) without considering radial distance or wind sector.

3.4.1 Particulate Matter

Table 4: Spearman's Rank Correlation between Particulate Matter Parameters and Elevation

Parameter	ρ	p-value
Deposition rate	0.3667	0.33174
Weight (g)	0.2833	0.46003

3.4.2 Soil Samples

No soil parameter was significantly correlated with elevation (all $p > 0.05$; Table 5), in contrast to water (Section 3.4.3); this contrast is interpreted below

Table 5: Spearman's Rank Correlation between Soil Parameters and Elevation

Parameter	ρ	p-value
Calcium ion	+0.3926	0.11901
Manganese	-0.3313	0.19396
Magnesium	+0.2900	0.25894
Sodium	-0.1838	0.48003
Potassium	-0.1704	0.51308
Chloride	-0.1704	0.51308
Lead	+0.1324	0.61237
Electrical Conductivity	-0.1288	0.62237
Phosphate	-0.0944	0.71851
Sulfate	-0.0895	0.73261
pH	+0.0832	0.75086
Chromium	+0.0737	0.77860
Phosphorus	-0.0588	0.82256
Nickel	+0.0393	0.88092
Cadmium	+0.0148	0.95519

3.4.3 Water Samples

Cadmium was the only nominally significant elevation relationship among every correlation reported in this study (verified across Tables 2–5 and Figures 3–4, and the accompanying text in Sections 3.2–3.4); the major rock-forming ions (calcium, magnesium) showed weak, non-significant relationships with elevation. However, this p-value (0.049) is uncorrected: with roughly 30 variables tested for elevation correlation in the water matrix alone, a Benjamini–Hochberg correction (critical threshold ≈ 0.0017 for the smallest-ranked p-value at $\alpha = 0.05$) would not preserve this result as significant. The cadmium-elevation finding should therefore be treated as a candidate signal warranting targeted confirmatory sampling, not as a statistically confirmed effect.

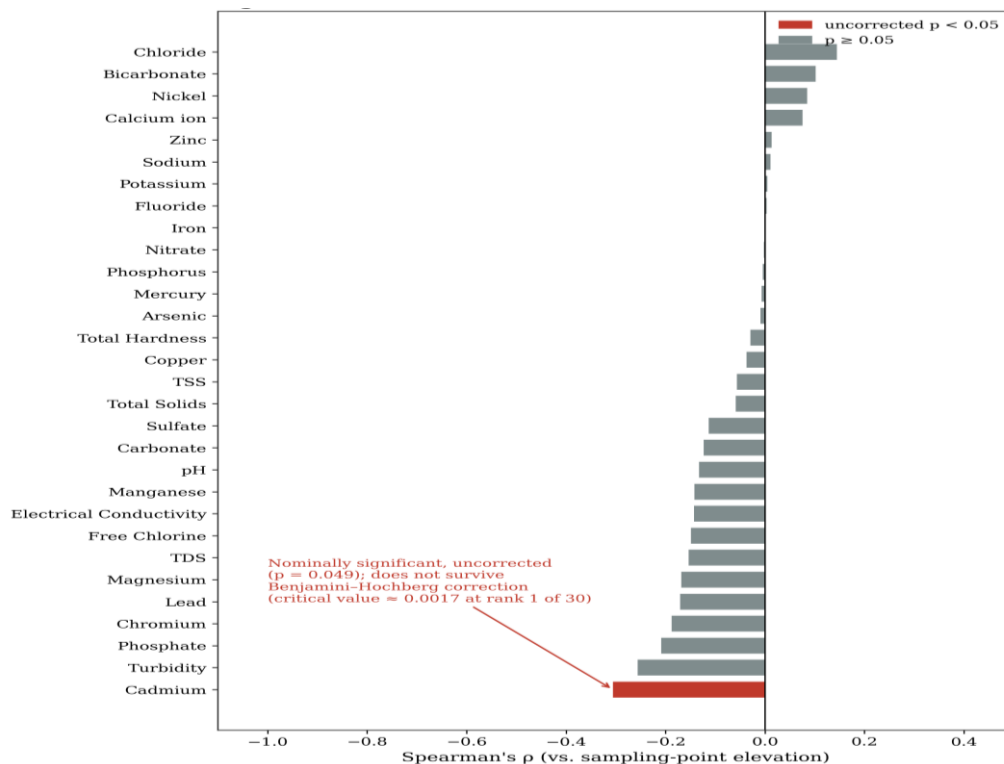


Figure 4: Spearman's ρ between water parameters and sampling-point elevation ($n = 30$). Cadmium is the only nominally significant relationship (uncorrected $p = 0.049$); this does not survive a Benjamini–Hochberg correction across the 30 variables tested (Section 3.4.3).

Elevation is an Independent Predictor of Water Contamination but not Soil Contamination.

The soil-water distinction is reinforced in the elevation-based analysis using another perspective. There were no significant differences in topsoil concentrations by elevation, as would be expected if the deposition mechanism (falling dust) were not sensitive to gravity-driven down-slope redistribution. This is not the case, however, for water cadmium, where there was a nominally significant negative correlation with elevation ($\rho = -0.3057$, uncorrected $p = 0.049$; Figure 4) — a result that does not survive a multiple-comparisons correction (see Section 3.4.3) — tentatively suggesting that contaminants may be moved toward lower elevations of the catchment when they reach the subsurface. This is the mechanism that is predicted by fundamental groundwater flow theory and one in which water, and the solutes it carries, flow from high hydraulic head to low hydraulic head; thus, water flow generally follows topography instead of horizontal distance from the sources of the mobile solutes (Freeze & Cherry, 1979). One plausible hypothesis, not directly tested here since only cadmium reached even nominal significance among the metals examined, is that cadmium is not unique in being subject to this topographic transport process but is simply the most sensitive regulated metal for detecting it, owing to its relatively high mobility and weak sorption compared to the other regulated metals measured; other metals might transport along the same path at a lower concentration or rate not detected at this sample size. This hypothesis would require dedicated testing — for example, comparing sorption-normalized mobility across metals — before it can be treated as an interpretation rather than a speculation. The non-significant elevation relationships for the major rock-forming ions (Ca^{2+} , Mg^{2+}) also support the interpretation of a relatively uniform lithological dissolution signal from the background water chemistry, with the elevation-cadmium relationship representing an anthropogenic, topographically-routed contamination signal. However, since the WHO guideline value for cadmium in drinking water is 0.003 mg/L, any low-lying groundwater area that is even modestly contaminated would be of practical concern for any wells or boreholes located in those areas and this sub-population of sampling points would be a reasonable priority for follow-up, higher frequency monitoring.

3.5 Implications for Environmental Monitoring and Risk Management

The results of these studies, in addition to their statistical value, are significant for the design and prioritization of monitoring programs for cement works and similar point sources. First, the strong downwind gradients that occurred for particulate matter and topsoil metals (Section 3.3) suggest that monitoring budgets should be used disproportionately along the prevailing downwind corridor, as opposed to monitoring in a manner that is even around the facility perimeter, because a few stations located downwind are likely to give a better sense of impact than a larger number of stations distributed without any consideration for wind direction. Second, the apparent buffering effect of the soil column (Section 3.3) indicates that soil sampling can at least be temporarily used as an early warning indicator of groundwater risk: heavy metals are likely to build up in soil long before reaching the aquifer, and therefore a soil monitoring program based on an increase in levels over time may be able to warn of impending catchments that may be in danger of contamination before groundwater is actually detected. Third, the elevation-related cadmium signal in water (Section 3.4) also supports topography-informed borehole placement, rather than boreholes sited solely for ease of access. Boreholes placed in low-lying areas of the catchment are more likely to intercept the mobile solutes, such as cadmium, that this study found to accumulate there — though, as noted in Section 3.4, this remains a preliminary signal pending confirmatory sampling. When combined, these three implications suggest an approach to monitoring explicitly based on meteorology and topography, and not simply management convenience or spatial uniformity, which may be applicable to other point-source polluters with similar emission-deposition-transport physics, such as the mining, metal smelting and thermal power generation sectors documented in previous studies (Bermudez *et al.*, 2010; Yang *et al.*, 2020; Parlak *et al.*, 2023).

4. CONCLUSION

This study shows that undirected radial distance from a point-source cement facility is an unreliable predictor of contaminant distribution in particulate matter, soil, and water. Wind-sector stratification substantially strengthened distance-decay correlations for particulate matter ($\rho = -1.000$, $n = 5$) and topsoil metals (ρ up to -0.800), a descriptive pattern consistent with atmospheric deposition following a directional rather than concentric pathway, though these stratified subsets are small and the pattern awaits confirmation with a larger downwind sample. Water, in contrast, correlated weakly with both distance and wind direction, but cadmium showed a nominally significant negative correlation with sampling-point elevation ($\rho = -0.3057$, uncorrected $p = 0.049$, which does not survive a multiple-comparisons correction), tentatively suggesting that once contaminants pass the soil buffer, topography rather than proximity to the source governs their movement toward the water table. For engineering practice, these findings support replacing uniform radial monitoring networks with a matrix-specific design informed by wind direction and topography around point sources.

The study is limited by small and uneven sample sizes across matrices and stratified subsets, a single dry-season sampling round, and the absence of a multiple-comparison correction, so marginal results ($0.05 \leq p < 0.10$) should be interpreted cautiously. Future work should extend sampling across seasons and additional downwind locations to confirm these gradients, apply a Benjamini–Hochberg correction when testing multiple parameters simultaneously, and pair soil-adsorption or leaching trials with local groundwater hydraulic-gradient data to directly test the soil-buffering and topographic-accumulation mechanisms proposed here.

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