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RESEARCH ARTICLE

Legal and regulatory challenges in controlling heavy metal and chemical pollutants in geochemical cycles

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ABSTRACT

Huge number of heavy metals and chemical contaminants are scattered all over geochemical systems and tested in the face of constant hazard of environmental quality, human health, and governmental control. The influence of the environmental matrices on the spatial distribution, mobility and retention of lead (Pb), cadmium (Cd) and arsenic (As) was studied in five sites with varying environmental peculiarities in terms of industrial, agricultural, mining and waste related activities. In this study, different conventional methods have been used to explore the contamination of heavy metals in an untreated industrial wastewater (field sampling) and after treatments with atomic absorption spectrometry technique performed in a laboratory using a batch of adsorption tests and multivariate statistical analysis. Results suggest there may be a high spatial variability in the concentration levels of metal with land use derived patterns and geochemical properties as likely principal contributors to site-specific variation. Correlation and regression analyses showed that pH and electrical conductivity influenced the mobility of metals, especially arsenic, to a greater extent. The metals retention by adsorption as well presented non-uniform other retention behavior able to be reflected in their environmental persistence and potentially different mobility. To identify the hotspots of remediation, spatialization was performed. Combining this and the results would show how a localized geochemical profiling is important toward improving of understanding about pollutants dynamic patterns, localities in environmental management. These findings are also favorable to the idea of injecting science into the law system; that legal interests would be able to protect both environment and regulatory. This may be suggested for the future study to scaling up the spatial and temporal investigation, inclusion of chemical speciation examination of metals analysis and application of advanced predictive model in assessment. It is also suggested in the analysis that data should be harmonized to meet geochemical interpretation in accordance with the international environmental law as in Basel and Minamata conventions in order to meet the standards of the management of pollutions. It raises the level of application of the environmental geochemistry considerations in policy options and transboundary governance frameworks, by emphasizing the legal factuality of scientific facts.

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1. Introduction

Chemical pollution and heavy metal have become a serious ecological issue that has interrupted the complicated system of natural geochemical cycles. The contaminants gain access to the environment via various man-made channels, including industrial releases, mining, agricultural effluent, and urban effluent of wastewater. Once released into the environment, heavy metals such as lead, mercury, cadmium and arsenic and chemical pollutants undergo complex routes in the soil, water and air. These are long lived, bio accumulative and prone to having cascading effects via the ecosystem and human health [1].

The cycle of elements on earth is known as the geochemical cycle, and it is the process of how nature recycles and redistributes the elements in the spheres of the earth, lithosphere, hydrosphere, biosphere and atmosphere. Moreover, chemical elements are also recycled between and among minerals, sediments, soils, water bodies and biota during these cycles. However, such natural processes are interrupted by introducing heavy metals and artificial chemicals into this balance. The pollutants may be adsorbed onto the surface of the minerals; they may be taken up by the plants and wildlife and lost into the ground water sources. These chemicals may find their way back to the surface waters, or re-emitted into the atmosphere, where they continue to exist in the environment decades to centuries [2].

These are long-lasting and non-biodegradable pollutants within the environment posing significant environmental management and health hazards to the populace. The heavy metals, such as these, do not fade away in a degradation process and may be more bio accumulable in certain geo chemical situations. The situation is more difficult as chemical pollutants (pesticides, industrial solvents, synthetic organic compounds and others) can be metabolized into more toxic metabolites. These chemicals have a direct impact on biodiversity, agricultural productivity and water quality because they build up in soils, sediments and in the biological tissues. Heavy metal pollution of food, water or air is quite dangerous to humans leading to neurological effects, kidney damage, cardiovascular disorders and reproductive developmental disorders. This therefore makes it more and more necessary to decrease their geochemical abundance through geochemical cycles [3].

The issue of heavy metal and chemical pollutions in geochemical cycles is not simple to solve. These pollutants have very dynamic geochemical interactions with the environment and this is determined by temperature, pH, redox status and the presence of other chemical species. Also, they are often moved between environmental compartments: soils, water, and the atmosphere, which is often facilitated by the abiotic processes, i.e. precipitation, erosion, and volcanic eruptions and thus their distribution is challenging to predict and control. This in turn requires the environmental monitoring, assessment and other policies that cut across different branches of science to monitor, measure, and comprehend how such pollutants act and consequently can influence biological entities across space and time [4].

In this regard, legal and regulatory provisions are leading in combating heavy metal and chemical pollution. Formalized national and international laws and standards have been established through the years that have been implemented in an effort to cut down on emissions, what is deemed acceptable and even give a mechanism of cleaning up and resources of remediation activities. In such regulatory activities, scientific research is important in establishing the causes of pollution, measuring consequences as well as in the design of more effective practices in the reduction or prevention of pollution. Nevertheless, these attempts have not so far addressed significant gaps in the regulatory arena. The inconsistency in jurisdictions, implementation and lack of resources is a common problem with the existing laws, which are inefficiently enforced. Moreover, the ever-evolving state of industrial processes and the new chemical compounds are produced quicker than they are regulated leaving no solution possibilities a continuation of the geochemical cycles contamination [5].

With the multiple causes of the extensive pollution of the environment through heavy metal and chemical pollution, as one of the few disciplines that uses efforts to address the situation, a pragmatic interface of the environmental science and law is cultivated. The knowledge of the appropriate geochemical processes is needed to develop reasonable legal principles, and credible regulatory structures will assist in ensuring that polluters will have to compensate their actions as well as that mitigation programs would have to be implemented across the board. The cooperation of scientists, policymakers, and the regulatory bodies can be used to draw a more efficient paradigm of controlling these pollutants. Pollution, the need to protect ecosystems, and ensure the safety of the population can be alleviated with the help of the integration of total environmental surveillance, advanced treatment methods, and strict control of the regulatory scene [6].

The heavy metal and chemical pollutants are a multi-dimensional threat to the environment and society due to persistence, mobility and harm. The mysterious oceans and vegetal transports of these pollutants on human terminate uses them a great deal more than the construction of garment among the geochemical cycles bedevils containment and, consequently, their removal of the aftermath. It needs a special impetus to enhance the science and regulatory frameworks. This will assist in solving the major issue of geochemical re-circulation of heavy metal and chemical pollution and will result in improved environment of sustainable and healthy existence.

1.1. The aim of the article

The article will examine the challenges and restrictions in the law that will fight against heavy metal and chemical pollutants in geochemical cycles. This activity is set to serve to clarify the interrelationships of environmental law and regulation nuances, the dynamics of the behavior of pollutants in the natural systems, and forces that construct these rules. It seeks to establish the reason why there are existing regulatory failures, and where opportunities can be sought towards improvement. Among the existing international and national legal tools, the article mentions, it also brings to the attention the current state and the critical gaps of these tools which make the proper control measures difficult. These gaps can be attributed to the inconsistency in enforcement, or a lack of harmonization between jurisdictions, or a difficulty with alleviating pollutants which cross environmental compartments, e.g. soil, water, and air, continuously.

There is also certain practical implication of the article, other than identifying the gap in regulation, which is that it tries to analyze the possible ways in which the new scientific discoveries and ways of innovating law can be utilized in order to ensure that the heavy metal and chemicals pollutants are better regulated. Using the theme of environmental science, toxicology, and environmental law, this paper explains why it is necessary to establish a systems approach of how legal mechanisms can be modified to effectively deal with bio persist and bioaccumulating pollutants that infiltrate geochemical cycles. Special attention is paid to the role that cross-border cooperation and international agreements will play in helping to reach a coherent response to pollution issues. However, this article is not meant to be just another argument for why people should criticize one more idealistic legislation but instead show the draft suggested by it can be modified into strengthening towards more effective seeks that are very useful both for what concerns communal and human health.

Through its discussion of the place of law in addressing the heavy metal and chemical pollutant problem, this paper hopes to provide a contribution to larger questions regarding sustainability from an environmental perspective, and the manner in which law can influence society's response to environmental threats. Through such an analysis, being simplistic in nature, aims at reinforcing the legal mechanisms of enforcement, enhancing the practice of enforcement, and encouraging the proactive regulation approaches that are sensitive to the dynamics of geochemical cycles and their interactions with systems.

1.2. Problem statement

There has been a growing urgency in regard to the problem of heavy metal and chemical pollution of geochemical cycles due to the persistence and accumulation of these pollutants and the translocation of such pollutants across environmental compartments of the Earth. The sources of these pollutants include a variety of anthropogenic activities such as industrial activities, mining activities and agricultural run-offs. After they are introduced, they enter a geochemical system and circulate in soil, water and air in an endless process of redistribution. Heavy metals and certain chemical pollutants do not dissolve through time as many other pollutants. Instead, they remain within the environment and occasionally become more bioavailable and toxic to the environment under certain geochemical circumstances. This dynamic and movement renders them hard to control and contain in distinct forms.

This has ensured that legal systems have struggled to keep up and be creative on how these pollutants can be controlled and this is because much of the current legal frameworks has not kept up with the comprehensive scientific knowledge on how these pollutants behave. Even the national and international laws, which dominate the arena to a large extent, are inconsistent as well as there are gaps in enforcement and overlap in jurisdictional gaps. Actually, in most of the cases, regulations fail to cover the concept of transboundary pollution - pollutants emitted in a single location that impact ecology and health thousands or hundreds of miles away. The lack of unification of the regulatory standards also complicates efforts to reduce the concentration of pollutants and protect the ecosystem.

In addition, the lack of connection between science and regulation is still very large. Although the role of significant pathways and mechanisms of pollutant transfer in the geochemical cycles have been outlined by the scientists, they are not always reflected in legal instruments and enforcement policies as far as allowed. The failure of science to inform the environment and law to do so can translate into missed chances of early intervention and save the day by more effectively regulating pollution. Consequently, metal- and chemical-related pollution are still one of the very big threats to the biodiversity, the sustainability of human health and natural resources.

The difficulties are not only that these pollutants are not only persistent and harmful, but that legal regimes are not necessarily the most effective in limiting their spread and consequences. In order to address it, we must bridge the gaps between scientific knowledge and legal instruments.

2. Literature review

Chemical and heavy metal pollution is a critical environmental challenge, and its negative impact on the ecosystem and human health is large. Therefore, much is known about the origin, routes and impacts of these pollutants in the geochemical cycles. Heavy metals, including mercury, lead, cadmium and arsenic are usually released during mining, industrial discharges and agricultural effluents. Similarly, other chemical pollutants, including pesticides, solvents, and industrial wastes are put into natural systems in the most common way through surface run-off or landfill leachate, or by direct disposal to water bodies. Once these pollutants are released into the environment, they last long, are not biodegradable and in some cases, the chemical structure of such pollutants is distorted to give rise to more toxic forms [7].

Some very primitive categorization of environmental pollutants can be: Particulate (soot, dust), soluble (salts, dissolved sulfates and nitrites) and gases (CO2, SO2, Ozone). Lithosphere, hydrosphere, atmospheric, and biosphere interactions are required to move these around the geochemical cycle. The pollutants may be trapped in the soil particles, adsorbed to the surface of minerals or carried to the ground water flow and rivers. Pollutants dispersing to a large distance are also through atmospheric deposition. The result of such dynamic processes is the continuous exchange of contaminants and other chemicals between the environmental compartments making it difficult to predict the rate of their concentration and impact with time [8].

Eco-toxicity research revealed adverse effects of these toxins on plant and animal and human health. Nurological damage, developmental delays and chronic diseases in humans are known to be caused by heavy metals. Cases of low biodiversity, reproduction cycles failures, and low growth of water and soil organisms have been associated in ecosystem environments with an increase in the level of pollutants. Chemical pollutions include synthetic organic chemical compounds that tend to bio-accumulate in the food chain and behave in an exaggerated manner at the higher troic levels [9], creating chronic ecological changes.

The regulatory programs and the environmental surveillance programs have since risen in reaction to set the levels of the pollutants, and to make the provisions of the pesticide's mitigation But, the gaps in the world of law and in the world of science are big gaps that are yet to be filled. The regulations do not normally cover emergent pollutants or the synergistic effects of several pollutants. Although scientific models become more complex, they do not overcome their incapability to predict the behavior of pollutants in various environmental conditions with a high level of accuracy. This incongruity of scientific understanding and application has been among the reasons behind a long struggle that has been put in trying to control heavy metal and chemical pollutants [10].

Past research has indicated the necessity to better match environmental science with legal/policy solutions to tackle these chronic pollutants in effective manners. This is a complementary method since the heavy metal and chemical pollution of geochemical cycles occurs across boundaries and thus is too complex to be considered by a single discipline.

3. Materials and methods

This study adopts a transdisciplinary methodological approach which is based on a combination of geo-environmental fieldwork, high-precision instrumental analysis, multivariate statistical modeling, and thermodynamically-derived adsorption kinetics to study the dynamics of heavy metal and chemical pollutants across geochemical interfaces [2, 4, 5].

3.1. Environmental sampling and field measurements

The stratified spatial sampling protocol was undertaken in five environmental stressed areas- each of which was chosen according to the prevailing anthropogenic activity (industrial, agricultural, urban runoff, mining, and waste deposition) [3, 7]. Each location was further stratified into a five-grid transect matrix (5) and randomization on a sub-grid basis was further done to reduce spatial autocorrelation.

Triplicate samples of soil, sediment, and surface water were taken using decontaminated corers and bailers at every grid point, which is in line with ISO 5667-3:2018. Onsite parameters consisting of pH, electrical conductivity (EC), temperature (T) and oxidation-reduction potential (ORP) were measured utilizing a multi-probe which was standardized against NIST standards.

Water samples were filtered on 0.45 um syringe filters made of PTFE and acidified to pH < 2 using ultrapure HNO 3. Air drying Solid samples were dried at 30degC, sieved (to less than 2 mm) and kept in inert polyethylene containers. All the samples were geotagged, archived and recorded in a geodatabase system to trace the spatio-temporal traceability [1, 8, 11].

3.2. Analytical quantification of heavy metals

Graphite Furnace Atomic Absorption Spectrometry (GFAAS) was used to measure the concentrations of Pb, Cd, and As because it was found to be more sensitive, as per the USEPA 6020B. Microwave-assisted acid digestion of samples was conducted in closed samples with 3:1 NHNO3:HCl under 180degC *and 800 psi* [12].

To determine accurate concentrations, we applied a multi-point external calibration with matrix-matched standards. The corrected absorbance (A_{corr}) was computed as:

$$A_{corr}=A_{sample}-A_{blank}-\sum_{i=1}^{n}\beta_i \cdot X_i \tag{1}$$

Where A_{sample} raw absorbance of the sample; A_{blank} instrument and reagent blank; β_i; spectral interference coefficient for interfering species X_i.

Metal concentration C was calculated using:

$$C=\frac{(A_{corr}-A_0)}{m} \tag{2}$$

Where A_0 is y-intercept from calibration; m slope of the calibration curve (sensitivity); C metal concentration in mg/kg (soil/sediment) or mg/L (water).

Limits of detection (LOD) and quantification (LOQ) were computed as:

$$LOD=3.33 \cdot \frac{\sigma_b}{m},\ LOQ=10 \cdot \frac{\sigma_b}{m} \tag{3}$$

where σ_b is the standard deviation of the blank and mmm is the calibration slope [13, 14].

3.3. Geostatistical and multivariate analysis

To evaluate spatial dependencies and variance across sample points, Ordinary Kriging was applied using a spherical semi variogram model:

$$\gamma(\mathrm{h})=\begin{cases} C_0+C\left[\frac{3\mathrm{h}}{2a}-\frac{\mathrm{h}^3}{2a^3}\right], & 0<\mathrm{h}\leq a \\ C_0+C, & \mathrm{h}>a \end{cases} \tag{4}$$

Where h lag distance, a range of spatial influence, C_0 nugget variance, and C partial sill.

This interpolation was used to visualize spatial metal gradients and identify pollution hotspots, consistent with prior work on geo-contamination modeling [2, 15].

To detect co-contamination patterns and infer common sources, Principal Component Analysis (PCA) was performed on z-standardized datasets. The eigenvalue decomposition of the correlation matrix R yielded loadings for each metal:

$$R \cdot V=\lambda \cdot V \tag{5}$$

Where R correlation matrix, λ eigenvalue (variance explained), V eigenvector (component loadings)[3, 16]

3.4. Regression and predictive modeling

To explore functional relationships between geochemical parameters (like pH, EC) and metal concentrations, multiple linear regression (MLR) and generalized additive models (GAMs) were employed. The MLR structure was defined as:

$$Y=\beta_0+\beta_1 \cdot pH+\beta_2 \cdot EC+\beta_3 \cdot T+\epsilon \tag{6}$$

Where Y response variable (metal concentration), $\beta_0,\beta_1,\beta_2,\beta_3$ are regression coefficients; ϵ residual error term

Model fitness was assessed via adjusted R2, Akaike Information Criterion (AIC), and Variance Inflation Factor (VIF) to address multicollinearity [17, 18].

3.5. Laboratory adsorption experiments

Batch adsorption isotherms were conducted to simulate sorption kinetics under controlled laboratory conditions. Soil samples (10 g) were equilibrated in 100 mL solutions containing varying metal concentrations (10–100 mg/L) at pH 6.5, 25°C, and 20% moisture content. Equilibrium was achieved at 24 hours with constant agitation.

Equilibrium adsorption data were fitted to the Langmuir and Freundlich isotherm models.

1. Langmuir model (monolayer sorption):

$$q_e=\frac{q_{max} \cdot K_L \cdot C_e}{1+K_L \cdot C_e} \tag{7}$$

2. Freundlich model (multilayer sorption):

$$q_e=K_F \cdot C_e^{1/n} \tag{8}$$

Where q_e metal adsorbed per unit mass of soil (mg/g); C_e equilibrium concentration (mg/L); q_{max} max sorption capacity; K_L, K_F Langmuir and Freundlich constants; n heterogeneity index [19-21].

The distribution coefficient (K_d) was calculated as:

$$K_d=\frac{q_e}{C_e} \tag{9}$$

Kinetics were modeled using the pseudo-second-order rate equation:

$$\frac{t}{q_t}=\frac{1}{k_2 q_e^2}+\frac{t}{q_e} \tag{10}$$

Where q_t is the amount of metal adsorbed at time t, and k_2 is the rate constant.

3.6. Quality assurance and method validation

All the instrumentation was calibrated before and after the analysis with certified standards. The types of batches that were analyzed were procedural blanks, matrix spikes, duplicates and certified reference materials (CRM). The criteria used to accept were:

- Instrumental drift: < ±0.05 Abs
- Relative standard deviation (RSD): < 5%
- Recovery efficiency: 95–105%
- Outlier rejection: via Grubbs' test at 95% CI

Internal QA/QC conformed to protocols established by Rozas et al. [13], Wang et al.[19], and Ogbeide & Henry [5].

It is a multi-layered approach that entails merging geochemical analytics with spatial statistics and kinetic modeling, which facilitates a scientifically robust basis of analyzing the behavior of pollutants within geochemical cycles, which is important to inform adaptive legal and regulatory systems [4, 6, 22].

4. Results

4.1. Heavy metal concentrations by site and matrix

The total estimation of heavy metal was therefore carried out at five bio-physically distinct sampling areas associated with excessive anthropogenic activities: Industrial effluents, agriculture run-off, urban effluent, mining activity and leachate waste. Soil, water and sediment were normalized for 6 metals i.e., lead (Pb), cadmium (Cd) and arsenic (As). This part of the section intended to describe concentration variation horizontally by site and matrix and this indeed, illustrates there is spatial and environmental heterogeneity with respect to secondary pollutants dispersion. All are GFAAS values and sample values in mg/kg (solid) or mg/L (aqueous). The investigations provide an underpinning of a geochemical hypothesis, statistical evidence and regulatory considerations.

Table 1. Heavy metal concentrations by site and matrix

Metal	Site A – Soil (Industrial Park)	Site B – Water (Agricultural Field)	Site C – Sediment (Urban Riverbank)	Site D – Soil (Mining Region)	Site E – Water (Landfill Zone)
Lead (Pb)	35.2	0.18	29.4	40.1	0.15
Cadmium (Cd)	5.7	0.02	3.9	4.8	0.03
Arsenic (As)	10.3	0.12	9.5	11.8	0.11

The results indicate a great difference in the levels of heavy metal among sites and matrices. Site D (Mining Region) recorded the highest lead level of 40.1mg/kg, which is likely a result of several years of metalliferous deposition. Site A (Industrial Park) had the maximum cadmium content (5.7mg/kg), which is likely attributed to the effluents of industries along site A and fallout. Site C showed high levels of all the three metals in the sediments which were suggestive of the favorable environment of deposition. Although the overall concentration was lower, cadmium and arsenic remained prominent in water samples and the agricultural and landfill areas were prominent in at least one sample that was linked to each area. These tendencies show that the type of matrices and land use are important to identify contamination patterns

4.2. Statistical descriptors and inter-site significance testing

The differences in environmental measurements were statistically proven by conducting a descriptive and inferential analysis. Environments included metal concentration, pH and conductivity. The statistical tools of mean, standard deviation, and variance can reveal how values of pollutants are distributed and how much activity can vary at different sampling points, and the levels of pollutants compared to ANOVA p-values will assist in deciding whether the difference that is observed is significant. This sub-section will attempt to interpret site-specific variability, assess the heterogeneity of the macroscale and microenvironment and measure the confidence of patterns that are identified in heavy metal distribution.

Table 2. Descriptive Statistics and ANOVA Significance

Parameter	Mean	Standard Deviation	Variance	ANOVA p-value
Lead (Pb)	30.0	4.2	17.6	0.03
Cadmium (Cd)	4.3	1.1	1.2	0.05
Arsenic (As)	10.7	1.3	1.7	0.02
pH	7.0	0.3	0.09	0.04
Electrical Conductivity	0.2	0.03	0.0009	0.01

The statistical test confirmed that there is large variation among sampling sites Lead concentrations had the highest variance (17.6) which shows that there is a great dispersion between high-exposure sites and control sites. The p-value of ANOVA is 0.03, which informs us that such differences are significant. Cadmium and arsenic also varied with more than 1 among the six sites (1.2 and 1.7 per site respectively) and with p-value of approximately less than 0.05. In the environmental impact domain, pH (+/−SD 0.3) span is the least but at least changes in EC had also a significance (independent with p-value 0.01) and therefore even small modifications of EC significantly influenced levels of the pollutant. This is a reason for further multivariate and predictive modeling.

4.3. Correlation between physicochemical parameters and metal concentrations

The relationship between geochemical factors and metal accumulation is significant for identification of the fate and migration of pollutants in natural environments. Pearson correlation coefficients of pH vs the concentration of metals and electrical conductivity vs the metals selected in reanalysis were calculated to establish linear correlations. These associations aid mechanistic understanding on sorption, leaching and ionic competition, in addition to providing a framework for risk mapping and regulation planning.

Table 3. Pearson correlation coefficients among parameters

Parameter Pair	Pearson Correlation Coefficient
pH vs. Lead (Pb)	–0.45
pH vs. Cadmium (Cd)	0.31
pH vs. Arsenic (As)	–0.28
Conductivity vs. Lead (Pb)	0.50
Conductivity vs. Cadmium (Cd)	0.62

The correlation analysis indicates that there is a moderate negative correlation between the pH and the lead concentration (-0.45) and this supports the hypothesis that solubility and mobility of led is higher in the acidic environment. There is also a less strong negative correlation between pH and arsenic (-0.28) and a positive relationship between pH and cadmium (0.31) which is relatively weak, which shows the different complexation behaviors. Electrical conductivity which is a proxy of total dissolved ions is positively correlated with cadmium (0.62) and moderately correlated with lead (0.50) indicating that ionic competition or salinity can be affecting the movement of these metals. The findings indicate that geochemical conditions play a critical role on the environmental cycling of toxic elements.

4.4. Adsorption behaviour of metals in soil systems

The batch adsorption tests were conducted under known laboratory conditions in order to simulate a natural soil-metal interaction and pollutant retention process. The equilibrium concentrations and the number of metals that is adsorbed and the distribution coefficients are presented in this section. On the whole this assists in determining the sorption affinities and similar immobilization of lead, cadmium and arsenic that may be useful in remediation decisions and are also useful in model the contaminant mobility in soils.

Table 4. Adsorption experiment results for metal retention in soils

Metal	Initial Concentration (mg/L)	Equilibrium Concentration (mg/L)	Adsorbed Quantity q_e (mg/g)	Distribution Coefficient Kd
Lead (Pb)	50.0	35.2	1.48	0.89
Cadmium (Cd)	20.0	12.3	0.78	0.68
Arsenic (As)	30.0	18.4	1.16	0.56

The adsorption findings revealed that lead had the greatest soil retention with an adsorption coefficient of 0.89mg/g and partitioned of 1.48mg/g meaning that lead was strongly affinity to soil particles probably through the precipitation or surface complexation mechanism. Cadmium was moderately retained (Kd = 0.68) and arsenic, more mobile but with a significant binding was also observed (Kd = 0.56). The reduced value of Kd of arsenic can also represent its weaker adsorption to soil colloids at near-neutral pH. Findings indicate that the design of the remediation strategies based on stabilization or immobilization should include metal-specific sorption behavior.

4.5. Predictive modelling of arsenic concentration based on geochemical parameters

In order to assess the predictability of each environmental variable to reflect the correlation between environmental variables and mobility of arsenic, we developed a multiple linear regression equation of the relationship between pH, electrical conductivity and temperature as predictors. It was created to estimate the degree to which the variability in the measured arsenic concentration in each of the environmental compartments would be explained by the variability in site specific geochemical conditions. Table 5 displays the model coefficients, their statistical significance and confidence interval.

Table 5. Predictive regression model outputs for arsenic concentration

Predictor Variable	Regression Coefficient (β)	Standard Error	t-Statistic	p-Value
Intercept	18.22	3.21	5.68	0.0003
pH	–2.38	0.61	–3.90	0.0021
Electrical Conductivity	45.17	12.05	3.75	0.0034
Temperature	0.42	0.33	1.27	0.225

The regression analysis of the chosen variables showed the most consistent result with pH and electrical conductivity tossing significant coefficients and temperature not being a statistically significant predictor with the level of p =.05. However, the negative value of the pH coefficient (-2.38) suggests that, as pH decreases, that is to say, as the environment gets acidic, the arsenic concentration in it also rises, which confirms the common phenomenon of desorption of nutrients on the soil colloid surface. Concerning the ionic strength, the positive coefficient (45.17) also proves that the increased ionic strength promotes the mobility of arsenic presumably through the following mechanisms: competitive sorption or dissolution enhancement. Large t-statistics and large p-values of these variables imply that they have a strong predictive power among these two variables, and hence their significance as important controls on arsenic geochemistry and transport.

5. Legal challenges governing heavy metal pollution

The regulation of heavy metal and chemical pollution at the crossroads between scientific evidences to support enforceable policy. Geochemical data is one of the most important inputs in environmental governance and its conversion into measurable criteria within a legally binding instrument is significant. A couple of international as well as national legal and regulatory frameworks constitute the cornerstone in controlling these pollutants and holding individuals to account.

At the international level, The Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal binds countries to manage hazardous metal containing waste by providing mechanism for prior informed consent and tracking of waste across borders [23]. The Minamata Convention on Mercury is a United Nations Environment Programme managed treaty addressing the abatement of anthropogenic emissions to protect human health and the environment from the adverse effects of mercury exposure from industrial processes and mining operations [24]. Conversely, the Stockholm Convention on Persistent Organic Pollutants includes various industrial chemicals that can act in synergy with metal pollutants [5].

At the regional level, the European Union (EU) Water Framework Directive (2000/60/EC) mandates member states to attain “good chemical and ecological status” of superficial water bodies and groundwater, prescribing acceptable levels for lead (Pb), cadmium (Cd), and arsenic (As) in industrial effluents [25]. It also includes emission limit values for dangerous substances from large industrial installations and requires operators to monitor heavy metal releases [26]. In the Iraqi context, it is a nation-wide legal approach for monitoring pollutant discharges with enforcement, and penalties where non-compliance to measures are made known (Environmental Protection and Improvement Law No. 27 of 2009) [27].

The measured concentration of lead in this study (40.1 mg/kg; mine site) is higher than the 20 mg/kg limit as specified by WHO and FAO standards, possibly pointing to a violation in terms on compliance with Law No. 27 of 2009 [27]. By incorporating science-based evidence in a regulatory framework, policymakers have the ability to focus remediation efforts and prosecute polluters with documented environmental records.

Further, experience abroad shows how scientific measurements might be used as legal evidence. In the Bug River in Poland full geochemical characterization of sediments served for more efficient monitoring and enforcement in conformity with EU water policy [2]. Furthermore, the existing one from Nigeria by Ogbeide and Henry is modified to reflect the importance of utilizing geochemical means in the improved identification of sources generating pollutants – a foundation for legal enforcement [5]. These illustrations are indicative for a proper management of geochemical contamination, which cannot be reached without legislation on monitoring and international standard setting environmental.

In addition to the above powerful tools, there are still issues that need to be addressed to further enforce uniformity in laws and regulation as well as incorporate scientific monitoring into day-to-day enforcement. These disparities highlight the need for legal standards to be adaptive and change as geochemical knowledge develops.

6. Discussion

The article provides an overall conception of the behavioral of heavy metals and chemical contaminants at the variety of geochemical environments, which confirmed the initial guess that determined states of core and localized individual sites as well as sequence with respect to chemistry are principal factors organizing imitation in time and space pollutants dispersion, mobility and fixation. Results The lead (Pb), cadmium (Cd) and arsenic (As) displayed obvious spatial heterogeneity, which was influenced by industrial, agricultural and mining activities. Those are consistent with the vast previous literature of the interaction between human-made inputs and natural soil or sediment processes in developing contamination patterns.

The increased levels of Pb found in soil samples in the mining area in this research concur well with those found by the researcher, Ke et al. [22] found comparable geographical distributions of soils in the lead smelting areas. We assume that our data demonstrate the long-term impact of such industrial activities because of the presence of metals in the environment, where the metals that don't get removed are remaining in the environmental compartments and influencing poorly buffered or acidic soil, even when the source of the metals is getting reduced. This correlation analysis yielding a strongly negative correlation of pH and lead concentrations, was broadly consistent with that of Zhao et al. [18] that demonstrated a lowering of pH leading to an increase in metal solubilization and mobilization in lake sediment matrices. These patterns in transitional environments such as the soil-water interface depict that a geochemical parameter acts as dynamic modulators of the pollutant availability.

Some comparative examples would show that data-driven governance makes the implementation of regulations better. Long-term geochemical mapping of the area of industrial Katowice (Poland) formed a foundation of application of the EU Environmental Liability Directive that stipulated that operators of industrial plants had to assume financial liability regarding soil and groundwater contamination that were more than the allowed pollution level The challenge of enforcement used to undermine robust legality laws in Niger Delta Nigeria is an example of how weak technical capacity and ineffective data networking may undermine accountability [5]. Equally, statistical spatial and multivariate analysis at the Mnasra agricultural plain, Morocco resulted in changes in the irrigation and fertilization laws, which combined geochemical evidence with feasible legal proceedings[3]. These examples indicate the need to bring environmental science and statutory law together so that contemporary pollution can be regulated.

In addition, the existing regression analysis showed that the pH and electrical conductivity could be good predictors of the arsenic concentration. It is in line with the chemometric modeling indicating that acidity is a major factor used in groundwater chemistry and contaminant movement at the coastal areas by Ullah et al. [16]. The present work expands this knowledge by mapping the correlations between these variables in the terrestrial matrices as well through statistically significant regression coefficients.

Experiments conducted in the laboratory through adsorption can assist in the development of the mechanistic knowledge of the metal retention behaviors. The sequence of adsorption coefficients was Pb >> Cd > As, as in the earlier study Golia et al. [20] the sequence of affinity was given in the discussion about the functions of soil texture, mineralogy and pH. Our findings show that Pb may sorb higher than Cr, which may be explained by one of the properties of Pb, which is capable of binding to organic matter and iron oxides, and therefore at the neutral pH; it will be less bioavailable. The trend is significant to the formulation of site-specific remediation strategies. Such examples are biochar and hydrochar amendments, which are also enhanced by Al-Swadi et al.[21] to increase the sorptive capacity of soils to such metals and offer low cost sustainable remediation techniques.

The analyses of spatial interpolation revealed the obvious hotspots of contamination in the mining and landfill sites, and therefore the utilization of geographic intervention strategies as the means of the remediation effect. These findings prove the findings by Tian et al. [28], and enhanced the spatial-temporal variability of cadmium in Guangxi, China, and the need to have spatiotemporal monitoring to inform remediation. Even though the dataset only represents a single sampling event, the consistent nature of the findings as to the presence of these zones as hotspots of pollution by various contaminants, validates their priority in terms of regulatory planning.

The article contributes to the development of understanding the behavior of pollutants in general, and to bridging between field studies and laboratory systems along a pyramid of environmental regimes. The exploration of this treasure trove of information, whether it be the field-based observations and experimental measurements to the statistical models and kinetic sorption experiments, is quite appropriate to the multidimensional character of the pollutant cycling in geochemical systems.

Nevertheless, it has a few limitations that can be mentioned. The first is that batch adsorption experiments simulate the situation of equilibrium but are unable to reproduce the dynamic changes in redox potential, microbial activity, and ligand competition that occur in the field. Additional complexities can be brought by zinc smelting related airborne deposition as according to Yu et al.[29], on top of geochemical baselines and potential fate of pollutants, which cannot be sufficiently forecasted by the use of a static model. Second, this research is limited by the geographical location and time-wise. Although there will be multiple matrices and sites, it will be restricted. Unlike models based on high-resolution time-related information as presented by Bai et al. [15], the study is not based on tracing the change of pollutants between seasons, or even years, an approach that may contribute to the interpretation under a varying climatic and hydrological condition.

Moreover, the research also failed to ensure the speciation of the metal because the influence of the metal is huge on bioavailability and toxicity. The data on speciation would have been useful towards the further clarification of the segregation of metals in the solid-bound form and the dissolved form. Furthermore, although cadmium and arsenic concentrations were measured in water, their speciation and complexation, especially as a function of redox states, were not considered, which may affect the accuracy of the risk prediction.

Dynamic behavior of pollutants in variable environmental conditions can be better explained using time-series data, speciation modeling, and advancement towards reactive transport simulations and is a possible avenue for future research. Wider coverage of geographical range, and an integration of geochemical data with biological and ecological proxies, would be a basis for a more robust approach to environmental risk assessment and legal action. Recent reviews covering such data-driven remediation frameworks [30] offer directions for how predictive machine learning models trained on larger datasets could also be developed to improve our ability to predict contaminant spread and inform revised policy design.

This study establishes that heavy metal and chemical pollution are multifactorial and demonstrates that effective legal and environmental governance needs scientifically-based, spatially-resolved and statistically-established environmental data. According to it, the behavior of pollutants is situational, and the legal norms and remedial methods must be adjusted to the geochemical situation. At the base of the ongoing struggles in addressing pollutants in the geochemical cycles, it is essential to address the gap in scientific information and its legalization.

7. Conclusions

that the movement and transport of metals, as well as other toxic chemical contaminants in geochemical systems, is governed by a sophisticated interaction between environmental physics and site-related parameters. Through analysis of soils, sediments and water at representative areas of anthropogenic impact we demonstrate that the spatial distribution of pollutants is not homogeneous but rather governed by local conditions indicative of land-use history, pH range, ionic strength and close-by industrial or agricultural inputs. This variation is a reminder that environmental pollution analysis should be site specific.

The secondary contribution of this work is the integrated methodology of field sampling-high precision instrumental analysis-laboratory simulation with rigorous statistics. The applied analytical approaches in the present study not only allowed the degree of pollution to be accurately determined, but also provided information on processes governing retention and mobility of pollutants. By that way, universality of some geochemical factors which control the pollution pathways was proven. Moreover, it provided evidence of in situ natural attenuation effects such as adsorption that may decrease pollution risk under certain circumstances.

And predictive equations of the two sets of relationships between meteorological parameters and heavy metal concentrations are built, showing that how can we use the geochemical index to predict the pollutant source. Risk assessment and monitoring strategies were discussed in MMF and FR, where pH and electrical conductivity represented key factors that determinant transport and distribution of arsenic (as) among other elements. These results suggest that predictive modelling approaches can help in supporting early-warning in environmental management.

Operating at a higher level of abstraction than engineering results, the research articulates concepts of pollution to non-engineering zones and between legal domains; in terms of regulatory conditions. Knowledge of polluted areas in previously industrialized or mined sections brings enforcement, compliance and environmental efficacy into question. A science-based model of regulations (based on observed measurements on environmental and geochemical parameters recorded continuously over time) could make the designs of the law more sensitive to real life.

However, potential future work to address these limitations would include an extrapolation of spatial and temporal scales for the sampling in order to improve the estimation of just how statement cycle pollutants over seasonal timescales due to climate. The explanation of ecological risk by ecotoxicologically relevant species could be related to ecological indicators. Shifting from the use of more advanced modeling tools like machine learning and geospatial analysis also allows for greater predictive capabilities and increases the amount of information available for remediation planning.

In addition to its scientific relevance, the study also serves as a model for determining the applicability of geochemical evidence in judicial and legislative proceedings. This is a job to be done when some government is wakened up to put such bodies in place, where the data on concentration levels of pollutants can be used as an officially accepted legal unit against which it should measure environmental quality. For example, predictive geostatistical models could be integrated into the EIA process risk-assessment model to provide early warning of non-compliance, and also as evidentiary baselines for liability. National authorities can also develop digital pollutant-tracing systems that connect field data with environmental licensure databases, culminating in real-time legal accountability. The measures are consistent with the trend of global development towards "information-oriented" environmental governance, and regulatory transparency follows from a commitment to scientific openness.

Moreover, compliance could be increased through mandatory geochemical certification of their soils and effluents before (re-)licensing. This has favoured EU Member States, and an analogous scheme could be tailored for accelerating economies of the developing world whose industries are growing apace. Environmental disclosure requirements are an important check against the risk of “greenwashing,” and they elevate public trust in environmental law. Grafted onto Iraq, these stereotypes may indeed come to transform the silent payola of compliance into a retrospective surveillance of evidence.

The findings of this study indicate that the long-term geochemical cycles do not have remedies working to relieve issues with heavy metals and chemical contaminants without being addressed on an interdisciplinary basis. A re-orientation is needed to integrate legal approaches, scientific evidence and environmental monitoring in a harmonious reflection for achieving sustainable development, public health protection and ecosystem resilience. They set the stage for scientific and regulatory innovation, providing a flexible approach to concentration levels in natural systems while recognizing that there may be circumstances where very specific numeric limits are appropriate.

Conflict of interest

The authors declare no conflict of interest

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