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Computational Analysis of Mercury Contamination in Gold-Bearing Soils and its Impact on Health of People

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Abstract

In this study, an exhaustive mathematical analysis of mercury transport in contaminated soils was carried out to clarify the extent of its environmental impact and possible remediation strategies. To this end, a rigorous mathematical model has been used, and a convergence and stability analysis has been carried out, considering a range of relevant parameters associated with mercury. This analysis involves discretizing the relevant differential equations, which allows us to quantitatively assess the impact of mercury on both the soil matrix and human health. The key findings of this study reveal that mercury concentration tends to decrease with soil depth. However, the environmental effects and implications for human health are significant. This analytical approach provides a deeper understanding of mercury dynamics in contaminated soils and crucial information supporting informed decision-making regarding remediation strategies and environmental and health risk management.

Keywords: *phytoremediation; contaminated soils; mercury; gold-bearing soils; discretization.*

1. Introduction

Our environment faces constant exposure to pollution due to the continued growth and expansion of industrialization. Despite the benefits that industries have brought to improving the quality of human life, such as energy generation and advances in the treatment of diseases, it cannot be ignored that these same industrial activities generate considerable environmental pollution, which adversely affects all living beings. An illustrative example within this context is the expansion of tree cultivation, which has experienced significant growth worldwide in recent decades. The growing demand for wood-based products essentially drives this expansion. However, this expansion of crops, which often involves intensive and highly mechanized methods, has led to the degradation of the soil's physical and hydrological properties. This degradation manifests

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itself primarily in the form of increased soil erosion and compaction, which in turn poses substantial challenges to the sustainability of agriculture [1].

In addition to soil problems, air pollution also raises environmental and public health concerns. Air pollutants, including particulate matter (PM), volatile organic compounds (VOCs), inorganic air pollutants (IAPs), persistent organic pollutants (POPs), heavy metals, and black carbon, can have adverse effects on the environment and human health, especially after prolonged exposure.

Of note, these airborne particles are not limited to specific areas; They can travel long distances in gaseous form and, as they are deposited, deteriorate air quality in areas far from the points where pollutants are generated. This underscores the need to effectively address soil and air pollution to preserve the planet's and its inhabitants' health.

Amid these challenges, phytoremediation emerges as a sustainable solution because it harnesses the natural ability of certain plants to absorb and detoxify pollutants in soil and water [2]. This practice has become valuable in restoring damaged ecosystems and mitigating environmental pollution. By allowing plants to absorb contaminants such as heavy metals and organic compounds, phytoremediation contributes significantly to the recovery of degraded soils, improved water quality, and restored areas affected by industrial activities.

Concerning mercury contamination in gold soils, concern about mercury contamination has grown due to the importance of this activity and the increasing volume of processes it has experienced [3], [4]. As gold mining has expanded, especially in regions rich in natural resources, the release of mercury into the environment has seriously threatened human health and the ecosystem. Mercury, a toxic metal, is widely used in artisanal and small-scale gold mining, and its harmful effects can have long-term repercussions [5]. This work will explore the causes and consequences of mercury contamination in gold-bearing soils and one strategy to mitigate this problem and preserve the integrity of these valuable ecosystems.

Gold mining in gold-bearing soils is a crucial economic activity for many communities, but it is often unsustainable, uncontrollably releasing large amounts of mercury as a byproduct. Mercury [6], in its metallic form, is highly toxic to aquatic life and, through bioaccumulation processes, can affect the food chain, putting the human populations that depend on these resources at risk. Researching and understanding mercury contamination in gold-bearing soils is essential to addressing the environmental and health challenges of gold mining. Through a detailed analysis of pollution sources, ecosystem effects, and remediation strategies, a comprehensive view of a complex problem can be provided. To that end, this paper seeks to expose the magnitude of the problem of mercury contamination in gold-bearing soils and a solution that can help mitigate such contamination and promote more sustainable gold mining. The conservation of gold-bearing soils and the reduction of mercury pollution are issues that require immediate action to ensure a sustainable future for both the environment and the communities that depend on these natural resources.

1.1. Basic processes for the recovery of contaminated soils

Remediation of contaminated soils is critical to restoring the health of ecosystems and preventing environmental and public health damage. Within phytoremediation techniques, there are several basic processes used in the recovery of contaminated soils:

Phytostabilization

This process focuses on reducing the mobility of pollutants in the soil and preventing their dispersion. It involves using plants that absorb and accumulate contaminants in their roots or tissues, decreasing the leaching of toxic substances into the environment. Plants selected for phytostabilization can hold contaminants in less mobile or toxic forms.

Phytoimmobilization

In this approach, plants are used to immobilize pollutants in the soil. The roots of certain plants release chemicals that can react with contaminants and turn them into less soluble or harmful forms. As a result, pollutants become trapped in the soil and become less mobile.

Phytoextraction

Phytoextraction is when plants accumulate high concentrations of pollutants in their tissues, especially in their roots. Once the plants have absorbed significant contaminants, they are harvested and removed from the site for safe disposal. This process is used to eliminate specific contaminants, such as heavy metals.

Phytodegradation

In phytodegradation, certain plants and associated microorganisms degrade organic pollutants present in the soil. Toxic substances are broken down into less harmful compounds due to metabolic processes in plants and roots.

Phytovololatilization

Some plants can absorb pollutants and release them into the atmosphere as vapor. This process is used to remove volatile pollutants, such as organic compounds. Phytovololactization helps reduce the concentration of contaminants in the soil, but it is important to consider air emissions management.

Rhizofiltration

Rhizofiltration refers to the process of filtering pollutants through the roots of plants. The roots act as a natural filter, trapping and adsorbing pollutants from groundwater or contaminated soils. This process is effective in removing dissolved contaminants in the water.

The choice of remediation strategy will depend on the type of contaminants present in the soil, the characteristics of the site, and the environmental conditions. As can be seen, sustainable alternative phytoremediation to address soil contamination sustainably and effectively.

1.2. Other related papers

The work of Khan et al. [7] discusses the different aspects of phytoremediation, including the selection of suitable plants, the factors affecting the efficacy of phytoremediation, and the biochemical and molecular mechanisms of plant adaptation to stressful conditions. Methods for evaluating the effectiveness of phytoremediation are also discussed, and some case studies are presented. The authors performed random sampling to obtain samples from different sites and to be able to complete a soil analysis to determine the presence of heavy metals and other contaminants, as well as moisture, total organic matter, saturation, electrical conductivity, phosphorus, potassium, and pH, then proceeded with acid digestion of soil samples and quantification of heavy metals by atomic absorption spectrophotometry and analysis of the physiological and biochemical parameters of plants, such as the accumulation of heavy metals and the production of antioxidant enzymes.

Other authors [8] consider the effects of heavy metal pollution on plant growth and photosynthesis processes, as well as the ability of phytoremediation to mitigate these effects. The study examines the morphology and development of plants exposed to different levels of heavy metal contamination and analyzes changes in photosynthesis processes. To measure the parameters of photosynthesis, a LI-6400XT photosynthesis meter was used. To calculate the chlorophyll concentration in the leaves, an 80% acetone solution was used, and the extinction of the extraction solution was measured at wavelengths of 663, 646, and 470 nm. An aqueous solution of 1% Na2S was also used to treat the plant samples before cutting them and observing them under a scanning electron microscope. It was observed that soil contamination by heavy metals hurts plant growth and photosynthesis. However, some plant species were found to have a higher tolerance to heavy metal contamination than others, suggesting that selecting suitable species may be necessary for phytoremediation. In addition, the study found that phytoremediation can be an effective solution to mitigate the effects of heavy metal contamination on plants and soil.

Zhou et al. [9] provide valuable information on the potential use of hyperaccumulators in phytoremediation, highlight the role of the ApHIPP26 protein in cadmium tolerance and accumulation in Arabidopsis thaliana, and evaluate its possible use in phytoremediation. To this end, ApHIPP26 overexposure experiments were performed on Arabidopsis thaliana plants. Under these conditions, the effect on cadmium tolerance and accumulation, gene expression, and antioxidant activity was evaluated. The study's results suggest that overexposure to ApHIPP26 can significantly improve cadmium tolerance and accumulation in Arabidopsis thaliana, which could have significant implications in the phytoremediation of soils contaminated with this type of heavy metal.

On the other hand, the reference [10] discusses herbicides widely used in agriculture and can contaminate soils and groundwater. The persistence of these herbicides in the environment can have toxic effects on human health and ecosystems. The study focuses on the biodegradation of these herbicides using emerging technologies, which can help reduce soil pollution and improve the quality of the environment. In addition, the importance of biotic and abiotic factors in the degradation of soil pollutants is highlighted, which may help better understand how the biodegradation of S-Triazine herbicides and other soil contaminants can be improved. The biodegradation of S-Triazine herbicides is a complex process influenced by various biotic and abiotic factors. The study highlights the importance of emerging technologies, such as nanotechnology and techniques focused on microbial active elements, in improving the biodegradation of herbicides and other soil pollutants. In addition, it is essential to understand better the degradation mechanisms of herbicides and other soil pollutants to develop effective biodegradation strategies and environmental monitoring.

Chauhan et al. [11] studied the soil microbiome and its relationship with plants. In this tour, they explore the diversity, benefits, and interactions of soil microorganisms with plants and how plant roots support the growth and functions of microorganisms. They also discuss the role of the soil microbiome in sustainable agriculture and ecosystem health, as well as the practical applications of soil microbiome research in improving crop productivity and soil quality. The work cited [11] mentions the ability of the soil microbiome for phytoremediation, which is the process of using plants and microorganisms to remove, degrade, or immobilize soil contaminants. In addition, it highlights how the soil microbiome can contribute to ecosystem health and agricultural sustainability, which can help prevent soil pollution in the first place. Overall, the soil microbiome is an essential component of the soil ecosystem and can significantly impact soil quality and environmental health.

Further research [3] assesses the risk of mercury exposure through fish consumption in the Amazon region of Brazil and provides relevant information to guide safe fish consumption in the study area. In addition, risk analyses were conducted to assess the relationship between mercury exposure through fish consumption and human health. We included a multivariate data analysis to identify risk factors associated with mercury exposure. The authors showed that mercury levels in fish were high. In addition, mercury levels were found to vary between different states in the Amazon region.

In the same vein, Kumar et al. [5] present on the pollution, bioaccumulation, and toxicity of mercury in various environments, providing information on the sources of mercury pollution, how it bioaccumulates in the food chain, and how it affects human health, as well as possible solutions to reduce pollution and its harmful effects.

These mercury pollutants are common in gold-mining areas, posing a significant challenge to environmental management and public health in these regions. The release of mercury often occurs during the gold mining process, where mercury is used to form amalgams with the precious metal. However, a considerable part of this mercury is not recovered and escapes into the environment, contaminating both soils and surrounding bodies of water. This type of pollution can also spread through the atmosphere and be deposited in more distant areas, expanding the scope of its impact.

Mercury in gold-bearing soils can seriously affect local flora and fauna and the communities that depend on these ecosystems for their livelihoods. In addition, long-term mercury exposure can harm human health, as this heavy metal bioaccumulates in the food chain and can reach dangerous levels in food consumed by people. Understanding and mitigating this type of pollution helps conserve the environment and the health of the populations that reside in these mining areas. In this context, it is necessary to comprehensively address the management of gold mining and reduce its environmental impact.

In this work, a mathematical model has been developed that shows the progress of mercury contamination in the earth bed to know the transport system of the pollutant and how it spreads in the soils. To this end, the mercury leaching and degradation analysis in a specific soil column experiment was addressed.

2. Materials and Methods

2.1. Preparation of the Model Sample

The model that allows the analysis of the leaching transport system and the degradation of mercury in the soil sample through the column experiment should be noted in this experiment was proposed in reference [12]. The investigation involves preparing a mixture of soil and mercury with a known initial concentration of 1 kg/m3. This mixture is confined in a cylindrical mold of 50 mm in diameter and a height of 20 mm. This sample is placed on top of a column of the same type of soil that will be analyzed. It should be noted that the sample column of uncontaminated soil must have a length of 280 mm and a diameter of 50 mm. As shown in Figure 1.

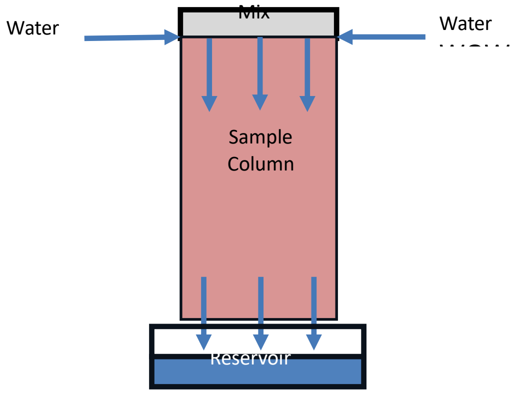

Figure 1. How the samples should be placed for the study's performance to measure the mercury agent's transport.

The contaminated mercury-containing sample's height is considered relatively small compared to the length of the column. It is assumed that the soil sample in the column must be saturated with water before placing the layer of the contaminated mixture. For this, a flow of water is supplied above the column, with a constant laminar-type flow, which induces the transport of the agent from the upper layer to the lower layer.

A leaching period of 2 days is recommended in a laminar flow with a velocity of 0.10 m/s. In the analysis, the extraction and processing of the samples for the following periods is considered: fifteen (15) and thirty (30) days, with a laminar flow of 0.0125 m/s. Installing a drain at the lower end of the column is essential to analyze how a pollutant behaves in a soil column. This drain facilitates water flow through the column, where a confined soil sample and a small sample of the contaminant mixture are located. As the pollutant moves, it is distributed between the liquid and solid phases of the soil and can be degraded by microorganisms in the soil. As a result of these processes, the concentration of the pollutant changes over time and in different parts of the column. This approach allows us to understand better how pollution spreads and is modified in a natural environment. During the experiment, the effluent is collected and analyzed. Subsequently, and after the periods mentioned above, the samples where the leaching has occurred are removed. The soil columns are sectioned into several layers, which are analyzed separately to know the level of advance and concentration for different depths as a function of the time it was exposed to the mercury-contaminated mixture.

2.2. Considerations of the proposed mathematical model:

- A constant flow rate is maintained in the water supply to the column-confined soil sample.
- A laminar flow is considered in the water flow supplied.
- The dispersion coefficient is considered constant.
- Advection and dispersion occur only in the vertical direction.
- The delay factor is independent of the concentration.
- Transformations in the liquid and solid phases occur at the same rate.

In the development of the experiment, the process was considered to model the leaching in a soil column exposed to advection and one-dimensional dispersion in a liquid phase, absorption towards a solid phase, and the biological degradation generated in the sample. Previous research has developed a mathematical model based on a balance in the sample mass. These equations are given by [13]for the proposed model.

$$\frac{\partial X}{\partial t} = \frac{\partial J_s}{dz} - k * X \quad (1)$$

Where

X is the total concentration of mercury (Kg.m^{-3}).

t is the time(s).

Js_is the total flow conveyed (Kgm$^{-2.}$ d^{-1}]).

z is the distance (m).

d is the degradation constant.

This constant rate is related to the half-life of the compound by X, t, z, k

$$T_{50} = \frac{\ln 2}{k} \qquad (2)$$

The total transported flow *Js* is the sum of the advective and dispersive transport:

$$\mathrm{J_s} = \upsilon.\theta.\mathrm{C} - \mathrm{D}.\theta.\frac{\partial \mathrm{C}}{\partial \mathrm{z}} \qquad (3)$$

Where

υ is the velocity of water ($m.s^{-1}$).

θ is the water content ($m^3.m^{-3}$).

C is the concentration resident in the liquid phase ($kg.m^{-3}$).

D is the coefficient of dispersion ($m^2.d^{-1}$)

Including the diffusion and hydrodynamic dispersion that is given by

$$\mathrm{D} = \mathrm{D_0}.\mathrm{k} - \alpha.\upsilon \qquad (4)$$

Where

D0 is the coefficient of diffusion in water ($m^2.d^{-1}$).

k is the factor of the terrain matrix.

α is the length of the scatter(m).

In this sense, the total concentration is equal to the sum of the concentration of the solid phase and the concentration of the liquid phase,

$$X = \theta.C + \rho.Y \qquad (5)$$

Being:

Y is the concentration in the solid phase ($kg.kg^{-1}$)

ρ is the density of dry mass ($kg.m^{-3}$).

Mercury in the liquid phase is considered to be in equilibrium according to a linear isotherm:

$$Y = K_{OC}.f_{OC}.C \qquad (6)$$

Where

K_{OC} is the reference adsorption coefficient of organic matter ($m^3.kg^{-1}$).

f_{OC} It is the organic matter contained ($kg.kg^{-1}$).

Combining equations from (1) to (6) yields the equation of general (7), which models the behavior of the system.

$$R.\frac{\partial C}{\partial t} = D * \frac{\partial^2 C}{\partial z} - \upsilon.\frac{\partial C}{\partial z} - R.C.k \qquad (7)$$

Where R is the retardation factor, defined by (8)

$$R = 1 + \frac{\rho.K_{OC}.f_{OC}}{\theta} \qquad (8)$$

2.3. Initial and Boundary Conditions.

The layer that initially contains the mercury is considered part of the column, and is incorporated under the initial conditions. The domain of the model is given from $z = -L$ to $z = \infty$, The initial conditions are:

$C(0,z) = C_0$ para un dominio $-L < z \le 0$ (9)

$C(0,z) = C_0$ para un dominio $0 < z \le \infty$ (10)

Where

C_0 is the initial concentration expressed in (kg m^{-3}), and L is the thickness of the first layer added to the earth column (m). Therefore, two boundary conditions are necessary. In the definition of the upper boundary condition, it is assumed that the water added in this part of the column is mercury-free. In addition, it is assumed that there is no decline of concentration in infinite depth. Therefore, the boundary conditions are given as shown in (11) and (12):

$$\nu.C*(-L,t) - D.\frac{\partial C}{\partial z}.(-L,t) = 0, \qquad t \geq 0 \qquad\qquad (11)$$

$$\frac{\partial C}{\partial z}.(\infty,t) = 0, \qquad t \geq 0 \qquad\qquad (12)$$

Other authors have previously considered similar initial and boundary conditions [14] [15]. Other initial and boundary conditions can be considered in studying mercury transport in soil columns for finite, infinite, and semi-infinite domains [16], [17].

3. Results

3.1. Solution of the General Transport Equation:

The equation of general (7), which describes the transport of mercury within the column of the soil sample, can be solved by applying finite differences with the Matlab software. Alternative methods exist, such as the Laplace transform or variable separation.

It can be seen that equation (7) can be discretized by applying methods of approximation by centered finite differences, applied to the partial derivatives of the first and second order by using the following equations:

$$C'(t,z) = \frac{C_{(t+\Delta t)} - C_{(t-\Delta t)}}{2*\Delta t} \qquad\qquad (13)$$

$$C'(z) = \frac{C_{(z+\Delta z)} - C_{(z-\Delta z)}}{2*\Delta z} \qquad\qquad (14)$$

$$C''(z) = \frac{C_{(z+\Delta z)} - 2.C(z,t) + C_{(z-\Delta z)}}{\Delta z^2} \qquad\qquad (15)$$

Substituting equations (13) and (15) into equation (7) yields:

$$\frac{C_{(t+\Delta t)} - C_{(t-\Delta t)}}{2.\Delta t} = \frac{D}{R}.\left[\frac{C_{(z+\Delta z)} - 2.C(z,t) + C_{(z-\Delta z)}}{\Delta z^2}\right] - \frac{v}{R}.\left[\frac{C_{(z+\Delta z)} - C_{(z-\Delta z)}}{2.\Delta z}\right] - C(z,t)*k \qquad (16)$$

$$\begin{aligned} C_{(t+\Delta t)} - C_{(t-\Delta t)} &= \frac{2.D.\Delta t}{R.\Delta z^2}\left[C_{(z+\Delta z)} - 2.C(z,t) + C_{(z-\Delta z)}\right] \\ &- \frac{2.v.\Delta t}{2.R.\Delta z}\left[C_{(z+\Delta z)} - C_{(z-\Delta z)}\right] - 2.C(z,t).k.\Delta t \qquad (17) \end{aligned}$$

$$\begin{aligned} C^{n+1} = \frac{2.D.\Delta t}{R.\Delta z^2}.\left[C_{i+1} - 2.C_i(z,t) + C_{i-1}\right] - \frac{2.v.\Delta t}{2.R.\Delta z}.\left[C_{i+1} - C_{i-1}\right] - 2.C(z,t).k.\Delta t \\ + C^{n-1} \qquad (18) \end{aligned}$$

3.2. Stability criterion

Once the discretization of the differential equation that defines the mathematical model in the study of the dispersion of mercury in the terrestrial bed of the sample has been developed, it is essential to restrict the size of the finite differences for the results to be conclusive in the analysis, for this study, the stability criterion shown in equation (19) was taken.

$$\frac{\nu^2.2\Delta\tau}{D.h^2} \leq 1 \qquad (19)$$

Where the differential time lapses of the experiment are taken into account, as well as the size of the differential element (h), which allows approximating by finite differences the characteristic curve of mercury dispersion in the sample, it should be noted that the refinement of the mesh allowed to obtain results with greater accuracy, by considering elements in more minor differences that guarantee numerical stability of the proposed mathematical model.

3.3. Convergence of results

As mercury penetrates the soil surface, its concentration is expected to decrease. This is due to the adhesion of mercury to the particles at the edges, the filling of the intergranular pores in the samples, and the influence of the normal force generated by the selection as the mercury progresses. In this way, a point is reached where these forces counteract the ability of the contaminant to advance in the soil sample, reducing its speed. Therefore, at specific depths and after a particular time, the power of mercury to run will be zero, and consequently, the level of contamination tends to be zero. This pattern will show up in the results.

3.4. Computational tool for modeling the advance of mercury in gold-bearing soils.

The system of transport of pollutants on the earth's surface has been the subject of extensive research by the scientific community, which seeks to model the behavior of the different types of contamination to minimize the ecological impact on the natural resources of our planet, even more so when such effect can compromise the health and well-being of living beings and the ecosystem.

Our mathematical model allows us to respond promptly by applying Matlab software as a computational tool to obtain a simplified answer to the concentration behavior in a soil sample. It should be noted that this solution is directly related to the previously defined edge and boundary conditions to facilitate the process of solving the model through the application of finite differences to respond to a model based on a second-order differential equation, previously defined in the research, and which allows to know the behavior of the pollutant in the selected sample.

The finite difference method applied to the convection-scattering equation for a problem under boundary conditions has already been studied by the scientific community, who have obtained solutions from the analytical point of view using advanced calculation techniques such as the Laplace transform and the integration by the method of separation of variables. However, unlike these investigations, in the development of this work, the finite difference method was applied using Matlab as a computational resource to obtain the solution of the equation. To do this, it was necessary to define and relate the properties of the soil sample as a whole with the properties of mercury presented in Table 1. The objective was to determine the second-degree differential equation's constants that predict the pollutant's behavior in the soil column used.

Table 1 Parameters of soil and mercury sample properties.

Parameter	Value	Units
L	variable	m
K_{oc}	0.100	$m^3 \cdot s^{-1}$
T_{50}	100	s
θ	0.40	-

$\upsilon\theta$	0.0125	$\mathrm{m} \cdot \mathrm{s}^{-1}$
D_0	4*10-5	$\mathrm{m}^2 \cdot \mathrm{s}^{-1}$
α	0.005	m
f_{oc}	0.01	-
ρ	1380	$\mathrm{kg} \cdot \mathrm{m}^{-3}$
k	0.34	-

Figure 2 shows that the mercury concentration in the soil column sample reaches its maximum concentration level in the first centimeter of depth in the column. After the first 48 hours, the concentration behavior begins to decrease until it reaches a depth of 40 mm, where the mercury concentration decreases in the sample. The concentration in the column tends to zero for depths greater than 50 mm, as seen in Figure 2.

Figure 2 shows the results obtained for a value of L= 0.01 m and t= 2 days.

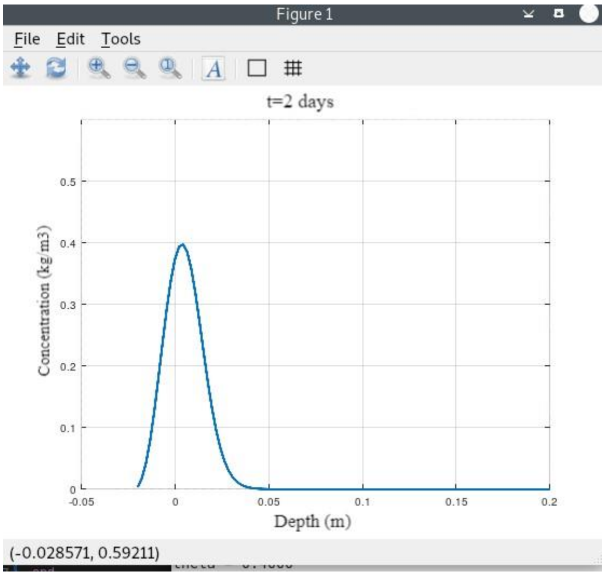

Figure 2. Concentration for L = 0.01, t = 2 days

For the analysis of the sample with an experiment time of 15 days, it was obtained that the pollutant reaches a depth of 0.09 meters with a concentration of 0.002 kg.m^{-3}, reaching its point of convergence tending to zero at a depth of 0.016 meters; that is, for depths more significant than the value mentioned above, it is expected that the concentration in that portion of the column presents values with a tendency to zero in the soil, as shown in Figure 3.

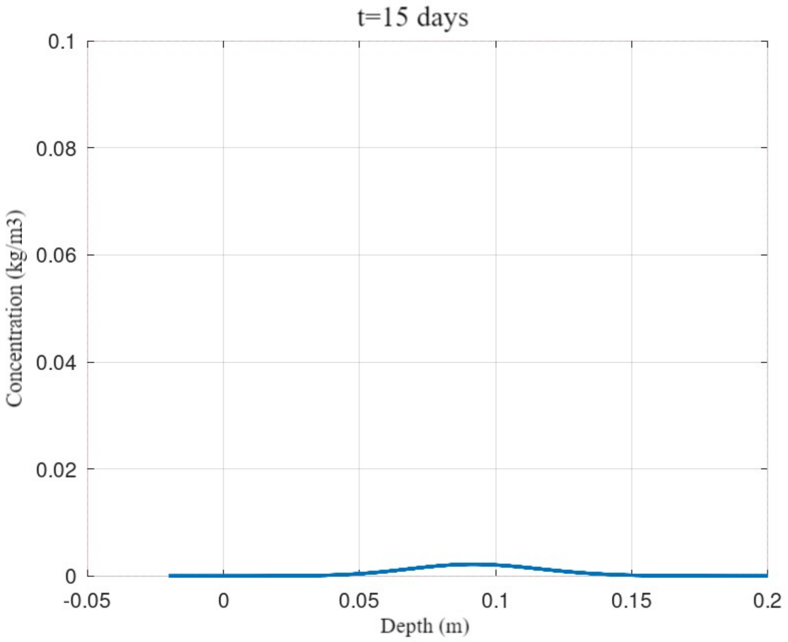

Figure 3. Concentration for L = 0.01, t = 15 days

The analysis of the third sample, for 30 days and exposed to the contaminant layer, can be seen in Figure 4. It is observed that the concentration is very close to zero for different depths within the sample range. It should be noted that, due to the continuous flow of the water flow within the soil column, with a relatively long period of study, it is expected that the flow of water and the intermolecular drag forces in the soil particles have generated a purification of the pollutant in the sample, which is dragged by the flow of water.

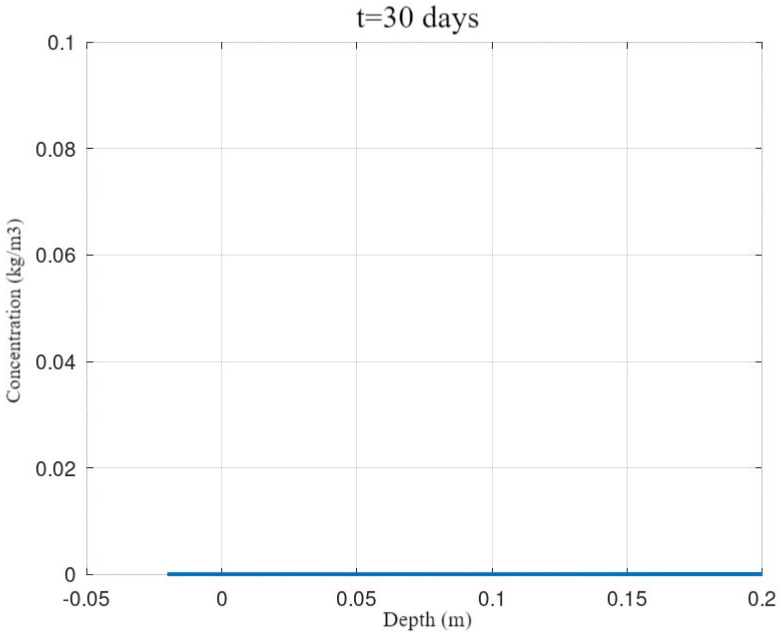

Figure 4. Concentration for L = 0.01, t = 30 days

4. Discussion

It is observed that initially, in the first 48 hours, the concentration is maximum at the surface (first centimeter deep) and then decreases as it deepens. This could suggest possible initial absorption or adsorption into the topsoil.

Figure 2 reveals valuable information about the dynamics of mercury concentration in a soil column over time and depth. A key finding is the presence of a concentration peak in the first centimeter of depth within the first 48 hours, suggesting an initial rapid absorption or adsorption of mercury into the topsoil. As we move deeper into the spine, the concentration gradually decreases, and a critical depth of 40 mm is observed where the decrease stabilizes. This required depth could indicate a natural barrier or a change in soil conditions that limits mercury migration to deeper layers. This pattern raises significant environmental and health issues. The high concentration of mercury in the topsoil could pose a potential risk, especially if this toxic substance comes into contact with nearby ecosystems or leaches into groundwater. In addition, Figure 2 underscores the complexity of biogeochemical processes in soil and the need for further research to understand in detail the factors influencing mercury distribution. Ultimately, this finding is a reminder of the importance of proper soil pollution management and the need to take action to prevent the release of mercury into the environment.

The result presented in Figure 3 is of great importance in the context of soil contamination and its evolution over 15 days. The data indicate that the pollutant under study has penetrated to a depth of 0.09 meters; at that depth, a concentration of 0.002 $kg.m^{-3}$ has been recorded. However, the most exciting thing is that the pollutant reaches its point of convergence towards zero at a depth of 0.016 meters. This suggests that, for depths more significant than this figure, the pollutant concentration tends to decrease and approaches near-zero levels. This observation has several implications. First, identifying the point of convergence to zero is valuable information, as it indicates the depth at which the pollutant can be effectively dispersed or degraded in the soil. This could be useful for decision-making in soil contamination management, as it could indicate how deep excavation or remediation should be in contamination cases. In addition, the contaminant concentration tends to zero for greater depths, highlighting the importance of monitoring and controlling contamination in surface soils, where the environmental impact and health risks are more immediate. In summary, Figure 3 provides critical information for understanding the dynamics of soil contamination and may have significant implications for environmental management strategies.

The results presented in Figure 4, which show a concentration very close to zero at different soil depths after 30 days of exposure to a layer of contaminant, are highly encouraging from the point of view of environmental remediation. These findings indicate that the continuous flow of water through the soil column has significantly impacted the purification of the contaminant present in the sample. It is suggested that intermolecular drag forces on soil particles, combined with constant water flow, have effectively removed the contaminant. This observation is critical to understanding how transport and reaction processes can contribute to the remediation of contaminated soils. In addition, these results have important implications for the design of remediation and environmental management strategies. Evidence that the continuous flow of water can purify the soil and remove the contaminant underscores the effectiveness of contaminated soil extraction and washing techniques that use this approach. However, it is also relevant to consider the proper management of the wastewater resulting from this process to avoid contamination and ensure a sustainable approach to environmental remediation. Taken together, Figure 4 offers an encouraging outlook for the remediation of contaminated soils through understanding the processes of water transport and purification in flow-through systems.

5. Conclusions

It was observed that the mercury concentration reaches its maximum at the surface and decreases with depth. It was shown that the concentration of a pollutant reaches zero at a certain depth. These observations highlight the importance of understanding the dynamics of soil contamination for effective management and developing remediation strategies.

The near-zero concentration at different depths after 30 days of exposure suggests that intermolecular drag forces and water flow have contributed significantly to removing the contaminant. This conclusion is essential for designing remediation strategies and highlights the importance of considering transport and reaction processes in managing soil contamination.

Computer simulation allows us to know how long the pollutant can last within the earth's surface and to obtain the maximum depth where its highest level of concentration is reached.

Computational analysis through finite difference allows us to know and model the resting time of mercury in the soil sample before being carried away by the flow of water that circulates within that sample.

The mathematical model proposed for analyzing the mercury transport system in the gold-bearing soils of artisanal mining facilitates the remediation of mercury-contaminated soils by knowing the maximum depth of the concentration level.

The tool is expected to be extended to different input parameters directly related to the data found on mercury in artisanal mining to make the valuable tool in studying the pollutant's transport phenomenon to various subsurface capacities to be analyzed.

The relevance of controlling and remediating contamination in surface layers to prevent environmental and health impacts is highlighted. Finally, the importance of addressing soil pollution proactively and sustainably is observed.

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