International Journal of Environmental Engineering Science and Technology Research
Vol. 1, No. 4, April 2013, PP:50-59, ISSN: 2326-3113 (Online)
Available online www.ijestr.org

**Research article**

# MODELING INHIBITION OF LEAD ON E.COLI GROWTH RATE IN SOIL AND WATER ENVIRONMENT IN OBIO/AKPOR, RIVERS STATE OF NIGERIA

**Eluozo, S. N.**

Subaka Nigeria Limited, Port Harcourt, Rivers State of Nigeria
Director and Principal Consultant Civil and Environmental Engineering, Research and Development
E-mail: Soloeluozo2013@hotmail.com
E-mail: solomoneluozo2000@yahoo.com

## Abstract

Modeling inhibition of lead on E.coli growth rate in soil and water environment in homogeneous unconfined aquifer has been developed. The models were derived through formulated governing equations, the expressions were derived in phases, and this is to monitor the system by considering all the parameters that influence the exponential phase of E.coli in soil and water environments. The formation under study is predominantly homogeneous deposition, the stratification in deltaic environment developed unconfined formation. This significant condition was considered in the system when the governing equation was formulated, the equation was derived and it developed model in accordance with behaviour of the microbes and other formation variables. Few model developed were integrated together, thus final expressed model was generated, the model expressed all the parameters based on the behaviour of the microbes at different formations. The expressed model will definitely monitor the migration of E.coli in unconfined aquifer, experts will find the model valuable because it shows that the concentration of microbial deposition in ground water aquifers are in exponential state, but can only experience degradation if there is no substrate deposition, thus, if there is high deposition of inhibitors in the study area. 

**Keywords:** modeling of lead E.coli growth, soil and water environment.

## 1 Introduction

The description of bacterial Coliform are base grouped, these are under the influences on common origin or characteristics, as either entirety or Fecal Coliform. The Total group includes Fecal Coliform bacteria such as *Escherichia coli (E .coli)*, as well as other types of Coliform bacteria that are naturally found in the soil. Fecal

Coliform bacteria exist in the intestines of warm blooded animals and humans, and are found in bodily waste, animal droppings, and naturally in soil. Most of the Fecal Coliform in fecal material (feces) is comprised of *E. coli*, and the serotype *E. coli* 0157:H7 is known to cause serious human illness.[*http://www.bchealthguide.org/healthfiles/index.stm*]

The existence of Fecal Coliform bacteria or *E. coli* indicates pollution of water with fecal waste that may restrain other harmful or disease causing organisms, including bacteria, viruses, or parasites such as *Giardia*, the cause of beaver fever. Drinking water contaminated with these organisms can cause stomach and intestinal illness including diarrhea and nausea, and even lead to death. These effects may be more severe and possibly life threatening for babies, children, the elderly or people with immune deficiencies or other illnesses.

Leachates quality varies throughout the operational life of the landfill and long after its closure. During the early stages of waste degradation and leachates generation the composition is acidic and high in volatile fatty acids (the acetogenic phase). These acid leachates may dissolve other components of the wastes, such as heavy metals. The leachate also contains high concentrations of ammoniacal nitrogen and has both a high organic carbon concentration and a biochemical oxygen demand (BOD). As degradation of the waste progresses conditions in the landfill become more anaerobic and the strongly reducing methanogenic phase is initiated. The majority of the remaining organic compounds are high molecular weight humic acids and the leachates are characterised by relatively low BOD values. Ammoniacal nitrogen generally remains at high concentrations in the leachates, but falling redox potential immobilises many metals as sulphides in the waste (Pohland *et al.*, 1993; Belevi and Baccini, 1992).Changes in other major ion concentrations may result from pH or redox changes in the leachates and interactions with the waste matrix. This is illustrated by a Stiff diagram (Tonjes *et al.*, 1995).

Lead is distributed in low concentrations in sedimentary rocks and soils. The average concentration of lead in shales, sandstones, and carbonate rocks is 20, 7, and 9 mg kg-1, respectively (Turekian and Wedepohl, 1961). Kabatas-Pendias and Pendias (1984) stated the background soil concentrations of 17-26 mg Pb kg-1 in the U.S. Anthropogenic enrichment of lead in near-surface soils stems largely from airborne deposition of particles derived from fossil fuel combustion (e.g., gasoline and coal). Lead is a common metal contaminant at hazardous waste sites, especially at battery crushing and recycling facilities (USEPA, 1991).

Sources of lead contamination to surface waters and ground waters include: fall-out of atmospheric dust, industrial and municipal wastewater effluent, mineral fertilizers and pesticides, lead-based paints, and wastes from the mining, metallurgical, chemical, and petrochemical industries. Lead is a widely used non-ferrous metal in the petroleum and storage battery industries. The fate of lead in the subsurface is controlled principally by adsorption at the solid-water interface, precipitation, and complexation with organic matter. Lead is strongly retained in soils and in most situations very little lead is transported to surface waters or ground water.

Fewer examples are found where remediation efforts have targeted lead contamination in ground water (Morrison and Spangler, 1993).Technology classes potentially applicable to the remediation of lead-contaminated soils include containment, solidification/stabilization, and separation/concentration (e.g., USEPA, 1997). Containment technologies applied at metal contamination sites include caps and vertical barriers to minimize the transport of lead and co-contaminants out of source zones. Amendments such as Portland cement or phosphate-based compounds are candidates for treatment of lead contamination in soils (e.g., USEPA, 1997).

Separation/concentration methods have also been used for lead treatment, including ex-situ soil washing and in-situ soil flushing to physically or chemically reduce contaminant concentrations to meet site-specific cleanup goals. Groundwater remediation of lead using the permeable reactive barrier technology has been explored with some success in bench-top studies (e.g., Shokes and Moller, 1999).

In a recent study of landfill leachates-polluted ground water containing up to 180 mg DOC L-1, more than 90% of the total lead in solution was present in DOC complexes (Christensen et al., 1999).Lead is usually not a metal of concern at mining-related sites where acid mine drainage is produced. This is because the weathering of metal sulfides, in addition, to generating acidity also produces high concentrations of sulfate, which results in the precipitation of anglesite (Zanker et al., 2002).

Lead hydroxide and lead oxide, although predicted to be stable based on thermodynamic reasoning, seem to be kinetically hindered from precipitating at room temperature (Marani et al., 1995). In sulfate-reducing systems, galena precipitation is thermodynamically and kinetically favored over a wide range of pH and total sulfide concentrations (Uhler and Helz, 1984).

Reaction between labile lead phases and dissolved phosphate is rapid over a wide range of pH and P/Pb molar ratios and results in the formation of insoluble chloropyromorphite (Zhang and Ryan, 1999).Lead phosphate minerals appear to be highly insoluble lead-bearing phases and remediation strategies for stabilizing lead-contaminated soils have taken advantage of this behavior (e.g., Ruby et al., 1994; Zhang et al., 1997).

Adsorption of trace metals, such as lead onto oxide surfaces, has been well characterized in lab-based studies (e.g., Hayes and Leckie, 1986). Hydrous ferric oxide (HFO) is of particular interest because it is found at many contaminated sites and could play a major role in governing the mobility of lead, other metals, and metalloids (e.g., Trivedi et al., 2003; Dyer et al., 2003). Lead adsorbs more strongly onto HFO compared to most other divalent metal ions (Dzombak and Morel, 1990); the same is true for other ferric oxides, hydrous oxides, aluminum oxides, oxyhydroxide, clay minerals, and poorly ordered Fe- and Al-containing hydroxypolymer coatings on natural aquifer sediments (Sposito, 1984; Coston et al. 1995; O'Reilly and Hochella, 2003).

## 2. Theoretical background

Mathematical model was developed by considering the E. coli growth rate function to be dependent of velocity, time, and distance of heavy metals and chromium concentration was applied, to predict the effect on E.coli growth rate. Based on these conditions stated above, a general mathematical expression can be written as: Lead deposition was found in an environment where there is waste dump sites, it is situated at industrial layout environments. The study area has a lots of company and waste generated and are dumped indiscriminately in some areas while some are dumped at government approved sites, but the waste generated from these companies in the study area are not treated, they are dumped indiscriminately and even the ones dumped at the designated site are not treated before disposal. This generated wastes generated have high percentage of industrial wastes than biological waste, waste are generated on a daily bases, the hazards generated from these wastes continue to deposit on the soil daily. Biological wastes generated from human settlements are in the same vein dumped, so the two types of wastes are deposited in the study area daily without proper handling. The rates of hazards generated daily continue to increase and affect thousands of people that settle in the area causing thousands of illnesses and deaths yearly. This menace are rapidly increasing every day thus most people are ignorant of what is happening.

This source of pollution is a serious concern to environmental health and need to be thoroughly addressed, the rate of lead and E.coli depositions were found from risk assessment carried out in the study area. These contaminants were confirmed to have deposited in the soil in a high percentage, due to constant dumping of these contaminants, the constant regeneration of these pollutants constantly accumulating on the soil. The study from hydrogeological point of view developed several variables that will always allow the deposition of these contaminants to migrate rapidly in soil and water environments, but in the course of this study they will be introduced in sequence so that their influence at various conditions on the migration of this contaminant will be thoroughly expressed. Results from hydro geological studies confirmed the study location to deltaic environment, the soil formations are found to be deltaic in nature; these expressed the other variables that influence the transport system of these two contaminants in the study area. The expressions from the dimensions are through mathematical model, equations were formulated that will govern the deposition of lead as inhibitors to E.coli growth rate in soil and water environment. The expressed equation considered the influential variable and the growth rate of E.coli in soil and water environment. The system considers the concentration from organic soil to ground water aquifer, formation characteristics influence on the deposition and migration were expressed in the system. The study area was found to be contaminated to a large area these developments were found through the dispersions of lead and E.coli in the formation. This implies that dispersion as a parameter will always play major role in the system. Therefore dispersions, was thoroughly expressed in the system; because the spread of the contaminants are through dispersions the governing equation are stated below.

## 3. Governing Equation

$$C(x)\frac{\partial v(x)}{\partial t} - D\ V^2 \frac{\partial C(x)}{\partial x} = \frac{V\partial C(x)}{\partial t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$ML^{-2}\ T^{-2} \qquad ML^{-2}\ T^{-2}$$

The expressed governing equations to monitor the migration of E.coli in the study area the developed equation express the E.cli condition in the formation, the generated equation were derived in stages base on exponential condition of the microbes, this express the behaviour under the influence of the stratification of the formation. Exponential of the microbes are influence by several parameters in soil and water environment, therefore the governing equation were derived considering the exponential state, this to ensure that the state of the microbes express in exponential are included in the system.

The equation (1) is non-homogenous process and can be written as

$$C_{(x)} \frac{\partial v(x)}{\partial t} - D_A v^2 \frac{\partial c(x)}{\partial x} = \frac{V \partial c(x)}{\partial t} \qquad \dots\dots\dots\dots\dots\dots \quad (2)$$

The expressed equation represent the state of the microbes on heterogeneous structural deposition, the formation at this condition influences the transport system of the microbes, the expressed equation were able to see other behaviour of the microbes in heterogeneous soil formation. The expression were able relate together with other parameters found to be influential in heterogamous formations, the rate on fast migration of E.coli behaviour are influenced by formation characteristic of the soil.

If equation (1a) is time dependent only, the equation reduces to:

$$C_{(x)} \frac{\partial v(x)}{\partial t} = \frac{V \partial c(x)}{\partial t} \qquad \dots\dots\dots\dots\dots\dots \quad (3)$$

Considering when the system is at steady state, the above equation (2) can be rewritten as:

$$D_A v^2 \frac{\partial c(x)}{\partial x} = 0 \qquad \dots\dots\dots\dots\dots\dots \quad (4)$$

The condition on the transport system were considered when the microbes are immobile in the system, this condition implies that there a tendency of the microbes accumulating or reducing in microbial concentration depending on the formation influence that increase the microbes or reduce it, the system express in such condition as zero.

For simplicity of solving equation (1), the following assumption is considered such as, let

$$C(x) \frac{\partial v(x)}{\partial t} = \beta \qquad \dots\dots\dots\dots\dots\dots \quad (5a)$$

Therefore, substituting equation (5a) into equation (1) becomes

$$\frac{V \partial c(x)}{\partial t} + D_A v^2 \frac{\partial c(x)}{\partial x} = \beta \qquad \dots\dots\dots\dots\dots\dots \quad (5b)$$

Equation (5b) can be rewritten as

$$\frac{V \partial c(x)}{\partial t} = - D_A v^2 \frac{\partial c(x)}{\partial x} + \beta \qquad \dots\dots\dots\dots\dots\dots \quad (6)$$

The systems in the condition express the behaviour of the microbes where by the system reposition there conditions, the accumulation of the microbes' to where it migrate experience dispersion, this condition implies that the contaminants at a certain level of transport are influence by high degree of porosity, this condition resulted microbes dispersing to a large area in the environment, contaminant are a menace to environmental health because when they experience pollution at a point due to formation influence on transport process, the microbial migration are spread to every part of the environments, this situation contaminate the ground water aquifer to a very large extend , there the microbes on dispersion influences will always increase the pollution to every part within the environment, deltaic nature of the study location will always experience this sources of pollution due the geological setting.

Equation (6) obtained can be resolved using mathematical application. In this research work the mathematical tools known as separation of variable was used in positive real number of $\lambda^2$ conditions. Thus, let

$$C(x) = Tx \qquad \text{(7a)}$$

Since $C(x) = f(Tx)$ therefore, differentiating (7a) with respect to time and distance yields the following mathematical expression

$$\frac{\partial c(x)}{\partial x} = T^1 x \qquad \text{(7b)}$$

It can be obtained from separation of variables

$$\frac{\partial c(x)}{\partial x} = Tx^1 \qquad \text{(7c)}$$

Therefore, substituting equation (7b) and (7c) into equation (7a) and further expression by substituting equation (8) into the obtained equation yields

$$V(T^1 x) = D_A v^2\ Tx^1 - Tx\frac{\partial v(x)}{\partial t} \qquad \text{(8)}$$

Expanding further we get

$$VT^1 x = D_A v^2\ Tx^1 - Tx\frac{\partial v(x)}{\partial t} \qquad \text{(9)}$$

Dividing equation (8) by *Tx* we have

$$\frac{VT^1 x}{Tx} = D_A v^2 \frac{Tx^1}{Tx} - \frac{Tx}{Tx}\frac{\partial v(x)}{\partial t} \qquad \text{(10)}$$

Thus, equation (10) can be written as

$$\frac{VT^1}{T} = D_A v^2 \frac{x^1}{x} = \frac{\partial v(x)}{\partial t} = \lambda^2 \qquad \text{(11)}$$

Equation (11) having taking the shape of separate of variable application as a mathematical tools used in solving complex problems of this kind.

Solving equation (11) term by term, we have

$$\frac{VT^1}{T} = \lambda^2 \qquad \text{(12)}$$

$$VT^1 = \lambda^2 T \qquad \text{(13)}$$

Applying the theory of Laplace transformation into equation (13) becomes

$$V(ST_{(s)} - T(o) - \lambda^2 T_{(s)} = 0 \qquad \text{(14)}$$

Considering the boundary condition as follows

*At T = 0*

$$T(o) \;=\; C_1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Therefore, substituting the boundary condition of equation (15) with equation (14) becomes

$$VST_{(s)} - VC_1 \;-\; \lambda^2 T_{(s)} \;=\; 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

$$VST_{(s)} - VC_1 \;-\; \lambda^2\ T_{(s)} \;=\; 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

$$VST_{(s)} \;-\; \lambda^2 T_{(s)} \;=\; VC_1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

$$(Vs -\; \lambda^2)\ T_{(s)} \;=\; VC_1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

Then $\dfrac{VC_1}{VS - \lambda^2}$ …………………. (20)

Therefore the Laplace inversion of equation (20) can be written as

$$T_{(t)} \;=\; VC_1\, \ell \frac{\lambda^2}{V} t$$

From equation (11) we have

$$D_A V^2 \frac{x^1}{x^1} \;=\; \lambda^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

Applying the same mathematical approach of Laplace transformation and considering the boundary condition at

$$X \;=\; 0$$

$$X(o) \;=\; C_2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Resolving the equation (21) by substituting the necessary boundary condition and using the mathematical equation as stated above given a general solution of

$$X_{(t)} \;=\; D_A V^2 C_2\, \ell \frac{\lambda^2}{D_A v^2} t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (23)$$

There an expression in (23) is a model generated with respect to distance travel on the transport process in the system, the system at these phase were express to be in exponential stage in the study location, this expression shows the rate at which dispersion under velocity of transport in the system, it also express its role on the exponential phase of the microbes in the model, the study area is waste dump environment, microbial concentration are always regenerating under the influence of constant indiscriminate dumping of waste and discharging of biological waste without treatment, so the state of exponential phase has experienced continuity in the study location

$$\frac{\partial v(x)}{\partial t} \;=\; \lambda^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (24)$$

Integrating the initial concentration for which $V \;=\; 0,\;\; V(o) \;=\; C_3$

$$SV_s - C_3 = \lambda^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

$$SV_s = \lambda^2 + C_3 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

Making $V_s$ the subject relation gives

$$V_s = \frac{\lambda^2 + C_3}{S} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

Using Laplace inverse we obtain

$$V_t = \lambda^2 + C_3$$

$$\lambda^2 = V_t - C_3 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

Therefore, from equation (20) where

$$T_{(t)} = VC_1 \ell^{\frac{\lambda^2}{V}t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

The expressed model (29) displayed it reaction on migration of the contaminants with respect to time, the concentration are monitored under the influence time. The system are under the state when the period of migration from one region to the are determined by the structural stratification of the soil, this can be attributed to variation of the deposition of the micropores in the soil formation, subject to this relation the behaviour from microbes under the influence of time are subject to void ration variation that determine the degree of porosity. The expression in (29) will monitor the microbes are under the influence time through the degrees of void ratio and porosity in the formation. The rates of migrations within a short period of time are determined by the degree of this two parameters in the system.

Therefore, substituting equation (20) into equation (20) becomes

$$T_{(t)} = VC_1 \ell^{\frac{V_{(t)} - C_3}{V}t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (30)$$

Similarly, substituting equation (28) into equation (23) becomes

$$X_{(t)} = D_A V^2 C_2 \ell \frac{V_{(t)} - C_3}{D_A V^2} t \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (31)$$

But

$$C(x) = TX = VC_1 \ell^{\frac{V_{(t)} - C_3}{V}t}$$

Therefore

$$C_{(t)} = VC_1 \ell^{\frac{V_{(t)} - C_3}{V}t} \bullet D_A V^2 C_2 \ell^{\frac{V_{(t)} - C_3}{D_A V^2}t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (32)$$

But $V = \dfrac{\partial}{t}$

Therefore, $t = \dfrac{\partial}{V}$ , thus equation (30) can be written as

$$C(x)_d = VC_1 \ell^{\frac{V_t - C_3}{V} \bullet \frac{d}{V}} \bullet D_A V^2 C_2 \ell^{\frac{V_{(t)} - C_3}{D_A V^2} \bullet \frac{d}{V}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

The model in (33) is the final model equation that express the exponential phase condition of microbial transport in soil and water environment, exponential state were express mathematically to monitor E.coli behaviour on progressive condition, the express governing equation were derived in phases, this is to descretize various dominant parameters, so that there functions on the microbial behaviour will be express. The express equation generated few models considering various phases, these depend on the behaviour of the microbes in there transport process. The significant parameters that may develop exponential condition in microbes deposition were expressed in the system, thus the model that express different conditions are base on the considered parameters that may cause exponential function to the optimum level, the benefit of these model developed in phases were to ensure that the conditions that causes exponential migration of microbes while migrating to ground water aquifers are expressed, finally all the model were attached collectively to developed the final model equation that will monitor E.coli in exponential phase in soil and water environment.

## 4. Conclusion

The developed equation that govern the migration of E.coli inhomogeneous unconfined aquifers has been expressed, modeling migration of E.coli growth rate in soil and water environments were formulated by considering the parameters that are significant to the system. The migration on exponential phase of E.coli in soil and water environments depend on the strata deposition in the study location, the developed equation were expressed in phases, the model were in stages according to their behaviour and formation of the soil, the parameters that is dominant are considered so that it will express its functions to the maximum level in the system. This is to ensure that the behaviour of the microbes at each phase is fully represented in the expressed model at every phase. The models were finally combined together to express the final model that will monitor the E.coli growth under the influence of lead inhibition in homogeneous unconfined aquifers.

## Reference

[1] Tonjes, D. J., Heil, J. H. and Black, J. A. 1995. Sliding Stiff Diagrams: A Sophisticated Ground Water Analytical Tool.*Ground Water Monitoring Remediation* Spring, 134-139.

[2] Pohland, F. G., Cross, W. H. and Gould, J. P. 1993. Metal speciation and mobility as influenced by landfill disposal practices. In: *Metals in Groundwater* (edited by Allen, H. E., Perdue, E. M. and Brown, D. S.). Lewis Publishers, Boca Raton, 411-429.

[3] Belevi, H. and Baccini, P. 1992. Long-Term Leachate Emissions from Municipal Solid Waste Landfills. In: *Landfilling Waste: Leachate* (edited by Christensen, T. H., Cossu, R. and Stegmann, R.). Elsevier Applied Science, London, 431-440.

[4] Marani, D., G. Macchi, and M. Pagano. Lead precipitation in the presence of sulphate and carbonate: Testing of thermodynamic predictions. *Water Research* 29: 1085-1092 (1995).

[5] Morrison, S.J. and R.R. Spangler. Chemical barriers for controlling groundwater contamination.*Environmental Progress* 12: 175-181 (1993).

[6] USEPA. *Selection of Control Technologies for Remediation of Lead Battery Recycling Sites*, EPA/540/2-91/014, U.S. Environmental Protection Agency (1991).

[7] USEPA. *Report: Recent Developments for In Situ Treatment of Metals-contaminated Soils*, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response (Draft) (1996).

[8] Shokes, T.E. and G. Moller. Removal of dissolved heavy metals from acid rock drainage using iron metal.*Environmental Science and Technology* 33: 282-287(1999

[9] Christensen, J.B., J.J. Botma, and T.H. Christensen. Complexation of Cu and Pb by DOC in polluted groundwater: A comparison of experimental data and predictions by computer speciation models (WHAM and MINTEQA2). *Water Research* 33: 3231-3238 (1999).

[10] Sposito, G. *The Surface Chemistry of Soils*, Oxford University Press, Oxford, UK (1984).

[11] Coston, J.A., C.C. Fuller, and J.A. Davis. Pb2+ and Zn2+ adsorption by a natural aluminum- and iron-bearing surface coating on an aquifer sand. *GeochimicaetCosmochimicaActa*59: 3535-3547 (1995).

[12] Dyer, J.A., P. Trivedi, N.C. Scrivner, and D.L. Sparks. Lead sorption onto ferrihydrite. 2. Surface complexation modeling. *Environmental Science and Technology* 37: 915-922 (2003).

[13] Dzombak, D.A. and F.M.M. Morel. *Surface Complexation Modeling: Hydrous Ferric Oxide.* John Wiley and Sons, New York, NY (1990).

[14] Trivedi, P., J.A. Dyer, and D.L. Sparks. Lead sorption onto ferrihydrite. 1. A macroscopic and spectroscopic assessment. *Environmental Science and Technology* 37: 908-914 (2003).

[15] Uhler, A.D. and G.R. Helz. Solubility product of galena at 298°K: A possible explanation for apparent supersaturation in nature. *GeochimicaetCosmochimicaActa*48: 1155-1160 (1984).

[16] Zhang, P. and J.A. Ryan. Transformation of Pb(II) from cerussite to chloropyromorphite in the presence of hydroxyapatite under varying conditions of pH. *Environmental Science and Technology* 33: 625-630 (1999).

[17] Kabata-Pendias, A. *Trace Elements in Soils and Plants*. CRC Press, Boston, MA (1984).

[18] Lindsay, W.L. *Chemical Equilibria in Soils*. John Wiley and Sons, New York, NY (1979).

[19] Turekian, K.K. and K.H. Wedepohl. Distribution of the elements in some major units of the Earth's crust.*Geological Society of America Bulletin* 72: 175-192 (1961