International Journal of Environmental Engineering Science and Technology Research
Vol. 1, No. 4, April 2013, PP: 70-78, ISSN: 2326-3113 (Online)
Available online www.ijestr.org

Research article

MATHEMATICAL MODELING OF SEEPAGE VELOCITY INFLUENCE ON MIGRATION OF DISSOLVED NICKEL IN WASTE DUMP ENVIRONMENT IN OYIGBO, 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

Mathematical Modeling of seepage velocity influenced by migration of nickel has been mathematically expressed. Seepage velocities are through structural deposition influenced by geological setting in the study location. Permeability and porosity in seepage velocity were found to develop several leaching of dissolved nickel contaminating ground water aquifers. These are found to take place within a short period of time, through constant regeneration of this contaminant. This has developed dispersions of nickel concentration in a very large area in study location**,** the model were derived through modified governing equation, expressed equation were developed considering the variables that influence the system, this concept were to express the variation of fluid flow based on the stratification that developed seepage velocity. Aquifers under the influence of porosity and permeability in the system were also expressed. Variation from fluid pressure were expressed with respect to period of flow, this has increased ground water contaminants through leaching of dissolved nickel. This include distance travelled to ground water aquifers and other existing influence in the formations, the study is imperative because the rate of fast migration of other substances are through the influence of regeneration of the solute, this substance also leach to ground water aquifers in the study area. They are influenced by formation characteristics such as porosity and permeability, the variables play major roles in fast transportation of solute, thus the degree of These two parameters determine the rate of variation of seepage velocity in soil, since variation in fluid flow determine several ground water conditions in soil and water**.**

Keywords: mathematical modeling seepage velocity, dissolved nickel and waste dump site.

---

1. Introduction

Industrial activity and natural environmental conditions have led to the introduction of nickel into soil and aquatic environments as a result of anthropogenic and geogenic sources, respectively (Duke, 1980; Richter and Theis, 1980). Nickel is a relatively minor constituent of the earth's crust having an average concentration of less than 0.01% by weight and ranking 24th in terms of abundance. Nickel is very heterogeneously distributed among crustal rocks ranging from less than 0.0001% in sandstone and granite to 4% in coveted ore deposits (Duke, 1980). Nickel can be found in igneous, sedimentary, and metamorphic rocks as well as nickel ores. In soils, nickel ranges from 5 – 500 mg kg-1 (Lindsay, 1979). Serpentine clay-rich soils are noted for natural geogenic abundance of nickel and have been the focus for use of hyperaccumulating plants to phytomine nickel (Chaney et al., 1995).

Nickel is one of the most mobile of the heavy metals in the aquatic environment. The mobility of nickel in the aquatic environment is controlled largely by competition between various sorbents to scavenge it from solution and ligands to form non-sorptive complexes. Although data are limited, it appears that in pristine environments, hydrous oxides and phyllosilicates control nickel mobility via co-precipitation and sorption. In polluted environments, the more prevalent organic compounds will keep nickel soluble by ligands complexation. In reducing environments, insoluble nickel sulfide may form.

The movement of nickel in ground water will be restricted by partitioning reactions to aquifer sediments. Probable techniques' that influences nickel partitioning to subsurface solids include direct adsorption to clay minerals, adsorption and/or coprecipitation with metal oxides, complexation with natural organic particles, ion exchange with charged surfaces, and direct precipitation as an hydroxide, carbonate or sulfide (Snodgrass, 1980). The chemical speciation of nickel in solution exerts a significant influence on the extent and mechanism(s) of partitioning to aquifer sediments, which may be influenced by acid-base reactions, oxidation-reduction reactions influencing the speciation of complexing inorganic solution species (e.g., aqueous sulfate vs. sulfide), and interactions with dissolved organic compounds. In general, inorganic/organic species that form dissolved complexes with nickel tend to enhance transport of nickel in soil profiles to subsurface water (e.g., dissolved organic carbon; Christensen et al., 1996; Warwick et al., 1997; Christensen and Christensen, 2000; Friedly et al., 2002). Field studies on transport in the subsurface illustrate several general conditions that are anticipated to result in expanding nickel plumes, including 1) acidic conditions (Kjoller et al., 2004), 2) manganese- and iron-reducing conditions (Larsen and Postma, 1997), and 3) the presence of mobile organic compounds that form soluble nickel complexes (Christensen et al. 1996; Kent et al., 2002).

Possible production concept that can be in a job for remediation of a ground-water plume containing nickel include physical removal of polluted soils or sediments that serve as a long-term source of nickel leached into ground water, extraction of the dissolved plume with some method of above-ground treatment, physical isolation of the dissolved plume, or in-situ treatment of a dissolved plume resulting in immobilization of dissolved nickel within the aquifer. Of these technologies, the use of permeable reactive barriers (PRBs) for the capture and immobilization of nickel plumes has been investigated and applied in field settings due to favorable performance and cost characteristics (Blowes et al., 2000). Both carbon- and metallic iron-based (or zero valent iron) reactive media have been employed for nickel removal from ground water. For carbon-based media, nickel removal is generally considered to occur through the precipitation of sulfide minerals, including nickel sulfides or coprecipitation of nickel with iron sulfides (e.g., Ludwig et al., 2002; McGregor et al., 2002).

There is also laboratory and field evidence that nickel immobilization can be enhanced through the addition of chemical amendments that promote nickel precipitation within soil or aquifer sediments (e.g., Lothenbach et al., 1997; Boisson et al., 1999; Seaman et al., 2001). The applicability and performance of these technologies will depend on the geochemical characteristics within the ground-water plume in conjunction with the velocities of ground-water flow and the flux of beneficial and non-beneficial reactive components transported within the plume.

2. Theoretical background

In observation of the complication of factors influential to water quality, and the large option of variables used to explain the position of water bodies in quantitative terms, it is hard to provide a simple description of water quality. Moreover, our perceptive of water quality has evolved over the past century with the expansion of water use requirements and the ability to measure and interpret water characteristics [UNESCO/WHO/UNEP, 996]. The evolutionary nature of chemical water quality issues in industrialized countries like Nigeria through the study area Oyigbo is a subject matter of concern, there are several water quality that are been determined, this include water quality assessment through laboratory investigations. Water is gotten from different sources for different purposes; furthermore narrative of the quality of the marine surroundings can be carried out in a variety of ways. It can be achieved either through quantitative measurements, such as physicochemical determinations (in the water, particulate material, or biological tissues) and biochemical/biological tests (BOD measurement, toxicity tests, etc.), or through semi quantitative and qualitative descriptions such as biotic indices, visual aspects, species inventories, odour, etc. These conceptual investigations are carried out in the field and in the laboratory and generate various types of information which provide themselves different interpretative techniques. For the purpose of simplicity the term “water quality” is used throughout, although it refers to the overall quality of the aquatic environment. [UNESCO/WHO/UNEP, 996] the rate of migration solute in soil and water environment are based on certain factor, these migration varies, because the level of transport is determined by stratification of the soil under the influence of geological formations’ of the study area. Seepage velocities in soil structural depositions are influenced by the sedimentation of the strata , the type of geological setting define the rate of seepage velocity that influence the migration of dissolved nickel in waste dump sites, nickel is one of the heavy metals found in our environment, this type of mineral are found to be hazardous to man, dissolve nickel in waste dump site implies that there is regeneration of nickel deposition in the environment. Constant deposition of the contaminant in the environment has resulted to high accumulation of this substance in soil and water environment. To monitor the rate of nickel deposition in a dissolved state, mathematical model were developed to determine the rate of concentration at every stratum in the study area. The governing equation is expressed below.

3. Governing equation

$$\frac{Vi\,\partial C}{\partial xi} = \frac{qi}{\varepsilon} = \frac{-Kih}{\varepsilon}\frac{\partial C}{\partial xi} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

$$\frac{\partial C}{\partial x} = SC_{(x)} - C_{(0)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (2)$$

$$\frac{\partial C}{\partial xi} = SC_{(x)} - C_{0} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3)$$

$$C = C_{o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (4)$$

The rate of dissolved nickel implies that there is constant deposition of the substance from man made activities, base on this condition expressions from equation (2) to (4) were transformed into Laplace, this is to express their functions to the level where the variables will express there relation to each other at different phases, under the influence of soil stratification that has deposited high degree of porosity at various soil formations, leaching of the substance to ground water aquifers are subject to this transformation, expressions were generated through the substitution below in equation

Substituting equations (2), (3) and (4) into equation (1) yield

$$Vi\left[SC_{(x)} - SC_{(x)} - C_{(0)}\right] - \frac{qi}{\varepsilon} - \frac{Kih}{\varepsilon}\left[SC_{(x)} - C_{(x)}\right] - C_{(0)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (5)$$

$$Vi\ SC_{(t)} - ViSC^{1}{}_{(t)} - C_{(0)} - \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}SC_{(0)} + \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}C_{(0)} - C_{(0)} \qquad \ldots\ldots\ldots\ldots \qquad (6)$$

Considering the following boundary condition at $t = 0,\ C^{1}{}_{(0)} = C_{0} = 0$ ……… (7)

We have

$$C_{(x)}\left(ViS - Vs - \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}S\right) = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (8)$$

$$C_{(t)} \neq 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (9)$$

The expression from equation (5) were to correlate the variables in the system with the transformation from equation (2) to (4) as expressed above, the relation with variables streamline the state of dissolved nickel through seepage velocity in several directions under the influence of formation characteristics in the system.
But considering the boundary condition

At $t > 0,\ C^{1}{}_{(0)} = C_{(0)} = C_{o}$ …………………………… (10)

$$SC_{(x)} - \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}S_{(x)} - Vi\,Sc_o + Vi\,C_o + \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

$$\left[ViS - \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}S\right]C_{(x)} = \left[Vi\,S + Vi + \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}\right]C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

$$C_{(x)} = \frac{Vi\,S + Vi\,\frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}}{ViS - \frac{qi}{\varepsilon}\frac{Kih}{\varepsilon}S}C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

Applying quadratic expression, we have

$$S = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

Where $a = Vi$, $b = \frac{qi}{\varepsilon}$, $c = \frac{Kih}{\varepsilon}$

To monitor the rate of seepage velocity in the system, an expression from Boundary values were integrated into the equation, this is to express the limits of seepage velocity under the influence of formation variations, through geological setting in the study area. The variables in the system that express influential roles were included to monitor the boundary of seepage velocity experienced in the stratification of the formation. This is to monitor other condition on fast migration of dissolved nickel to ground water aquiferous zones. Such expression implies that the seepage velocity will definitely experience high degree of dissolved nickel concentration under the influence of the variables in the system. The rate of variation through the influence of the deposition are observed from the rate of porosity that deposit in the study area. Equations (13) and (14) through the boundary values were integrated with other the functions that influence the variation of seepage velocity in the system.

$$S = \frac{\frac{qi}{\varepsilon} - \sqrt{\frac{qi}{\varepsilon}^2 + 4Vi\frac{Kih}{\varepsilon}}}{2Vi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

$$S_1 = \frac{\frac{qi}{\varepsilon} - \sqrt{\frac{qi}{\varepsilon}^2 - 4Vi\frac{Kih}{\varepsilon}}}{2Vi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

$$S_2 = \frac{\frac{qi}{\varepsilon} + \left[\sqrt{\frac{qi}{\varepsilon}^2 + 4Vi\frac{Kih}{\varepsilon}}\right]}{2Vi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

$$S_1 = \frac{\frac{qi}{\varepsilon} + \left[\sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]}{2Vi} S_2 + \frac{\frac{qi}{\varepsilon} - \left[\sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]}{2Vi} \ell^{\frac{\left[\frac{qi}{\varepsilon} + \sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]^{\frac{L}{v}}}{2Vi}} +$$

$$\frac{\left[-\frac{qi}{\varepsilon} - \frac{qi}{\varepsilon}\sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]}{2Vi} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

Applying inverse of the equation, we obtain

$$C_{(x)} = \left[\frac{Vi}{x} + Vi + \frac{qi}{\varepsilon}\right] C_o\, \ell^{\frac{\left[\frac{qi}{\varepsilon} + \sqrt{\frac{qi}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]^{x}}{2Vi}} + \ell^{\frac{\left[\frac{qi}{\varepsilon} - \sqrt{\frac{qi}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]^{x}}{2Vi}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

But if $x = \frac{t}{v}$

$$\left[C\,[t,v] = \frac{Vi}{t/v} + Vi + \frac{qi}{\varepsilon}\right] C_o \ell^{\frac{\left[\frac{qi}{\varepsilon} + \sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]^{\frac{t}{v}}}{2Vi}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

Considering the following boundary condition at

$$t = 0, C^{1}{}_{0} = 0, C_0 = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

$$C_{(x)} = \left[\frac{Vi}{x} + Vi + \frac{qi}{\varepsilon}\right] C_o\, \ell^{\frac{\left[\frac{qi}{\varepsilon} + \sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]^{\frac{t}{v}}}{2Vi} + \frac{\left[\frac{qi}{\varepsilon}\sqrt{\frac{qi^{2}}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}}\right]^{\frac{t}{v}}}{2Vi}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

At $C^{1}{}_{(0)} = t \neq 0$

Again $C_{(0)} = C_{(0)}$

The expressions of Boundary conditions were incorporated on the application of quadratic expression; this is to monitor the deviation in seepage velocity with respect to change in distance through formation characteristics that influenced ground water aquifers. These expressions are in line with other boundary values that were applied above. Subject to this relation, expressions that determine the variation of seepage velocity in this phase are based on variation of formation characteristics of soil stratification, under the influence of geological setting in the study location. .

So that $C_O = \left[Vi + \frac{qi}{\varepsilon} \right] C_o \, [1+1] \; i.e. \; 0 = \left[0 + \frac{qi}{\varepsilon} \right]$ ………………………… (23)

$$\Rightarrow \quad \frac{qi}{\varepsilon} + \frac{qi}{\varepsilon} = 0 \qquad \text{…………………………} \quad (24)$$

So that we have

$$C_{(x)} = \left[2\frac{Vi}{x} \right] C_o \, \ell^{\frac{\left[\frac{qi}{\varepsilon} \sqrt{\frac{qi^2}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}} \right]^{\frac{t}{v}}}{2Vi} + \frac{\left[\frac{qi}{\varepsilon} - \sqrt{\frac{qi^2}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}} \right]^{\frac{t}{v}}}{2Vi}} \qquad \text{…………………………} \quad (25)$$

However, $e^x + e^{-x} = 2Cos\, x$ therefore, we have

$$\boxed{C_{(x)} \left[2\frac{Vi}{t} \right] C_o \; Cos \, \frac{\left[\frac{qi}{\varepsilon} \sqrt{\frac{qi}{\varepsilon} + 4Vi\frac{Kih}{\varepsilon}} \right]^{\frac{t}{v}}}{2Vi}} \qquad \text{…………………………} \quad (26)$$

The expression in (26) defined the final model equation that will monitor the rate of seepage velocity, this were found to influences fast migration of dissolved nickel to groundwater aquiferous zone. Dissolved nickel regenerate from constant dumping of wastes in the study area. The derived mathematical equations were generated through the governing equation; the equation expressed will monitor the concentration rate of dissolved nickel to groundwater aquifers. Variation influence from several formation characteristics within a short period of time has been a serious concern to environmental experts. This is because a lot of ground water should be thoroughly examine, due to the rate of contamination from dissolved metal in soil and water environment, this condition has generated several illness from these type of pollution sources, because the rate of dissolved nickel should be observed to examine when the migration of such pollutant through fluid transport and contaminate ground water aquifers. The study of seepage velocity is imperative because knowing the rate of nickel deposition in the environment were waste are deposited will made the experts ensure that risk assessment are carried out. These concepts will ground water integrate factor of safety in design to prevent water pollution from the sources. To monitor this type of contaminant, mathematical model that will prevent this type of pollution were developed. The negligence from this direction has also resulted to a lot of water-related diseases which investigation of the cause were ignored in the study location. Variation of seepage velocity were found leaching the contaminant through the flow pathways, this condition play a major roles in the migration of solute, therefore the rate of seepage velocity in dissolved nickel can not be overemphasis, this is through variation structural deposition of soil formation, therefore the model for seepage velocity that influence the migration of dissolved nickel generate more influenced by permeability and porosity, subject to this relation with the migration of solute in soil formation, the direction of fluid flow through seepage velocity has been thoroughly evaluated in terms of its role in the system.. the developed mode will assist to engineer to monitor the rate of solute deposition resulting to the victims of pollution source that several cause illness in the study location, groundwater are the major source of water for human utilization, thousands of people in the study area got their water from public water supply and private boreholes. Subject to this relation, the rate of water related diseases cannot be overemphasized due to this ugly.

4. Conclusion

Variation of seepage velocity are determined by numerous factors, the velocity of seepage velocity are through soil geological setting, this is through stratification of soil deposit, they are influenced by the degree of porosity and permeability of the formation. The study area are predominant with deltaic formation, this condition implies that the formation has a lot of environmental influences through climatic condition, including the activities of man. Seepage velocity were found to influence dissolved nickel transport to ground water aquiferious zone, the study area experienced regeneration of this substance and this increased the concentration to a large distance and area; the rates of pollution migrating to ground water aquifer are the subject of concern in the study area. these are influenced by seepage velocity on the flow path, more so, formation characteristics through the micropoles at high degree of depositions were also confirmed to influence variation of seepage velocity, this condition determine the rate of fluid flow variation in strata to ground water aquifers. These concepts are expressed in the study through hydrological studies, information from hydrological studies are confirmed to express several formation characteristics that influences the deposition of seepage velocity and dissolved nickel in the study area. Such formation characteristics deposit several fluid pressures as presented in shallow aquifers, the deltaic nature of the study location deposit homogenous soil formation, this condition implies that fluid dynamics in soil are found to be predominant as expressed in deltaic environment. To monitor the rate of variation of seepage velocity in the study area, mathematical model were found to be the absolute concept that determines the rate of seepage velocity in the study area. The models were derived through the governing equation developed to solve the problem, the governing equations were derived considering several conditions that influence the variation of fluid flow through seepage velocity in deltaic environment. The derived mathematical model will monitor the variation of seepage velocity that influence dissolved nickel in the study area.

References

[1] Deborah C 1992 Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring - Second Edition United Nations educational, scientific and cultural organization world health organization United Nations environment programme

[2] Boisson, J., M. Mench, J. Vangronsveld, A. Ruttens, P. Kopponen, and T. De Koe. 1999). Immobilization of trace metals and arsenic by different soil additives: Evaluation by means of chemical extractions. *Communications in Soil Science and Plant Analysis* 30: 365-387.

[3] Blowes, D.W., C.J. Ptacek, S.G. Benner, C.W.T. McRae, T.A. Bennett, and R.W. Puls. Treatment of inorganic contaminants using permeable reactive barriers.*Journal of Contaminant Hydrology* 45: 123-137 (2000).

[4] Christensen, J.B. and T.H. Christensen. The effect of pH on the complexation of Cd, Ni and Zn by dissolved organic carbon from leachate-polluted groundwater. *Water Research* 34: 3743-3754 (2000).

[5] Christensen, J.B., D.L. Jensen, and T.H. Christensen. Effect of dissolved organic carbon on the mobility of cadmium, nickel and zinc in leachate polluted groundwater. *Water Research* 30: 3037-3049 (1996).

[6] Chaney, R., S. Brown, Y. M. Li, J.S. Angle, F. Homer, and C. Green. Potential use of metal hyperaccumulators.*Mining Environmental Management* September: 9-11 (1995

[7] Duke, J.M. Nickel in rocks and ores. In *Nickel in the Environment.*J.O. Nriagu (Ed.), New York, NY, John Wiley& Sons, pp. 27-50 (1980).

[8] McGregor, R., S. Benner, R. Ludwig, D. Blowes, and C. Ptacek. Sulfate reduction permeable reactive barriers to treat acidity, cadmium, copper, nickel, and zinc: Two case studies. In *Handbook of Groundwater Remediation Using Permeable Reactive Barriers.*Academic Press: New York, pp. 495-522 (2002).

[9] Lindsay, W.L. *Chemical Equilibria in Soils.* New York, John Wiley and Sons, pp. 211-220 (1979).

[10] Lothenbach, B., G. Furrer, and R. Schulin. Immobilization of heavy metals by polynuclear aluminum and montmorillonite compounds.*Environmental Science and Technology* 31: 1452-1462 (1997).

[11] Ludwig, R., R.G. McGregor, D.W. Blowes, S.G. Benner, and K. Mountjoy. A permeable reactive barrier for treatment of heavy metals.*Ground Water* 40: 59-66 (2002).

[12] Seaman, J.C., J.S. Arey, and P.M. Bertsch. Immobilizationof nickel and other metals in contaminated sediments by hydroxyapatite addition.*Journal of Environmental Quality* 30: 460-469 (2001).

[13] Snodgrass, W.J. Distribution and behavior of nickel in the aquatic environment. In *Nickel in the Environment.*J.O. Nriagu (Ed.), New York, John Wiley & Sons, pp. 203-274 (1980).

[14] Warwick, P., A. Hall, J. Zhu, P.W. Dimmock, R. Robbins, L. Carlsen, and P. Lassen. Effect of temperature on the nickel humic acid equilibrium reaction.*Chemosphere* 35: 2471-2477 (1997).

[15] Friedly, J.C., D.B. Kent, and J.A. Davis. Simulation of the mobility of metal-EDTA complexes in groundwater: The influence of contaminant metals. *Environmental Science and Technology* 36 3: 355-363 (2002).

[16] Kjoller, C., D. Postma, and F. Larsen. Groundwater acidification and the mobilization of trace metals in a sandy aquifer. *Environmental Science and Technology* 38: 2829-2835 (2004

[17] Kent, D.B., J.A. Davis, L.C.D. Anderson, B.A. Rea, and J.A. Coston. Effect of adsorbed metal ions on the transport of Zn- and Ni-EDTA complexes in a sand and gravel aquifer.*Geochimica et Cosmochimica Acta* 66: 3017-3036 (2002