Study of heavy metals transport in the vadose zone of contaminated soil

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ABSTRACT

Due to the anthropogenic activity, the soil environment is deteriorated by various organic and inorganic contaminants to a greater extent in Bangalore industrial area. The movement of heavy metals in soil is driven by various physical and chemical properties of the soil. This soil contamination leads to groundwater pollution through infiltration. In this study, an attempt is made to simulate the transport of heavy metals like nickel and zinc for one of the contaminated sites of Bangalore. The existing site contamination levels are used in the model to simulate the movement of nickel and zinc in the vadose zone of the soil. The simulation is carried out for 25 years to study the changes in nickel and zinc levels in infiltrated water considering the non-linear adsorption model. The simulation results help in identifying the vulnerability of groundwater borewells to these contaminants and in arriving suitable measures to prevent groundwater pollution.

Keywords: heavy metals, soil contamination, simulation, groundwater pollution.

1 INTRODUCTION

The heavy metal pollution in the water and soil environment is increasing at an alarming rate in both the urban and rural areas these days. The excessive use of pesticides, fertilisers, improper disposal of industrial effluent, land application of treated sewage and effluent, application of biosolids and sewage sludge have become the major sources of heavy metal pollution in soil and groundwater (Kumar et al., 2019). The excess concentration of heavy metals in soil can lead to bioaccumulation and groundwater pollution through migration (Tiwari et al., 2007). In developing countries like India, lack of proper guidelines and regulations has increased the rate of soil pollution at an alarming rate. The recent initiative by the Ministry of Environment Forest and Climate Change (MoEFCC) and Central Pollution Control Board (CPCB) to build inventory on contaminated sites lead to the identification of 320 sites as probably contaminated sites. According to this report, the major pollutants in the contaminated sites are found to be chromium, lead, copper, mercury, cadmium and arsenic. The major source for these contaminants in soil is the disposal of industrial effluent and hazardous waste (MoEFCC, 2015). The heavy metals can reach receptors (humans and animals) through different pathways like soil, air, surface and groundwater. The transport of contaminants in soil is primarily driven by the physical and chemical characteristics of the soil (Dos Santos et al., 2013). Advection, dispersion, sorption and degradation are the major transport process responsible for the migration of contaminants in soil (Sharma and Reddy, 2004). The leached heavy metals pose a higher risk of contaminating groundwater resources. Hence understanding the fate and transport of these heavy metals in the vadose zone helps in formulating strategies to protect the groundwater resources and in remediating the contaminated soil (Disli, 2010).

Several researchers have used various mathematical models to study the migration of heavy metals in soil. HYDRUS is one such software tool that helps in the simulation of water, solute and heat transport in variably saturated soil media. It solves the Richards equation for water flow, the advection-dispersion equation for solute transport and heat transport equation numerically within a finite element mesh (Simunek et al.,2012). In this paper, an attempt is made to simulate the transport of heavy metals, nickel and zinc in the vadose zone to understand its migration/contamination potential in the Peenya industrial area, Bangalore.

2 METHODOLOGY

2.1 Site Description

Peenya industrial cluster is located at 13° 1’42” N and 77° 30’45” E of north-western suburbs of Bengaluru city and covers an area 40 km\textsuperscript{2}. Peenya is one of the largest industrial area in Asia with many small, medium and large-scale industries. The major industries found in this region are hard chrome industries, electroplating, textile dyeing and pharmaceutical formulations, etc. The average annual rainfall in the Bangalore region is around

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923 mm. The major part of the industrial area has red sandy soil at 1 to 2 meters below the natural ground level. The industrial sector does not have any specific buffer zone separating it from the residential area.

### 2.2 Simulation

The governing flow equation for uniform Darcian water flow under variably saturated porous medium is given by the modified form of the Richards equation:

\[
\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_i} [K(h) \left( \frac{\partial h}{\partial x_i} + \frac{\partial K(h)}{\partial h} \right)] - S(h) \tag{1}
\]

where \( \theta \) is the volumetric water content [L^3/L^3], \( h \) is the pressure head [L], \( S \) is a sink term [T L^-1], \( x_i (i=1,2) \) are the spatial coordinates [L], \( t \) is time [T], \( K(h) \) is the unsaturated hydraulic conductivity function [LT^-1]. The van Genuchten unsaturated soil hydraulic characteristics equation is given by:

\[
\begin{align*}
\theta(h) &= \begin{cases} 
\theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^{n}]^m} & \text{if } h < 0 \\
\theta_s & \text{if } h \geq 0
\end{cases} \tag{2}
\end{align*}
\]

\[
K(h) = K_s \frac{S_{\epsilon}^2}{1 - \left(1 - S_{\epsilon}^{1/m}\right)^m} \tag{3}
\]

\[
m = 1 - \frac{1}{n}, \quad n > 1 \tag{4}
\]

where \( \alpha \) and \( n \) are empirical coefficients affecting the shape of the hydraulic functions, \( \alpha \) is reciprocal of the air entry pressure [L^-1], \( n \) is slope of the retention curve at the inflection point [-], \( S_{\epsilon} \) is the effective saturation [-], \( l \) is pore connectivity parameter [-], and \( \theta_r, \theta_s \) and \( K_s \) are the residual, saturated water contents [L^3/L^3] and the saturated hydraulic conductivity [LT^-1], respectively.

The advection-dispersion equation considering only sorption for the solute transport is given by:

\[
\frac{\partial q}{\partial t} + \frac{\partial \rho q}{\partial x_i} = \frac{\partial}{\partial x_i} [\theta D_{ij} \frac{\partial c}{\partial x_j}] - \frac{\partial \rho q c}{\partial x_i} \tag{5}
\]

Where \( c \) and \( s \) represents the solute concentrations in the pore water and solid phase respectively [ML^-3], \( q \) is the \( l \)th component of the volumetric flux density [LT^-3], \( \rho \) the soil bulk density [ML^-3] and \( D_{ij} \) is the dispersion coefficient tensor [L^2T^-1]. The adsorption of metals by soil is assumed as non linear Freundlich Isotherm and the same can be given by

\[
S = K_F L^\beta \tag{6}
\]

Where \( K_F [L^3 M^{1-\beta} M^{-1}] \) and \( \beta [-] \) are empirical coefficients of the Freundlich equation.

The data on the existing concentration of nickel and zinc in the soil medium is collected from the Karnataka state pollution control board (KSPCB) (Ratnakar et al., 2018). The data is then used to simulate the migration of nickel and zinc using HYDRUS 2D. The initial concentration profile used for simulation is given in Table 1. The parameters used for simulation are presented in Table 2. The average annual rainfall of the 10-year rainfall data amounts to 923 mm/year. The average monthly rainfall is used in the simulation as a variable flux input and top boundary condition is set as atmospheric. The transport domain of 100 cm wide and 300 cm depth is considered for simulation. The observation nodal points at every 50 cm are chosen to study the migration of the contaminants. The notation of observation node points are N1 = 0 cm, N2 = 50 cm, N3 = 100 cm, N4 = 150 cm, N5 = 200 cm, N6 = 250 cm and N7 = 300 cm. The entire simulation is carried out for 25 years. The transport domain details are shown in Fig 1.

**Table 1. The existing concentration of heavy metals.**

| Heavy metal | 0-30 cm | 30-90 cm | 90-150cm |
|-------------|---------|----------|----------|
| Nickel, mg/kg | 188 | 69 | 158 |
| Zinc, mg/kg | 368 | 33 | 40 |

**Table 2. Parameters used for simulation.**

| Parameter | Value |
|-----------|-------|
| Bulk Density, g/cm^3 | 1.5 |
| Residual water content | 0.065 |
| Saturated water content | 0.41 |
| Saturated hydraulic conductivity, cm/day | 106.1 |
| \( \alpha \), soil water retention function l/cm | 0.075 |
| \( \beta \), the soil water retention function | 1.89 |
| 1, pore connectivity parameter | 0.5 |
| \( K_F \) for Nickel, cm^3mg^1/3g^-1 | 6.4^x |
| \( \beta \) | 0.95^x |
| \( K_F \) for Zinc, cm^3mg^1/3g^-1 | 3.3^x |
| \( \beta \) | 0.65^x |
| Longitudinal dispersivity, cm | 30^x |
| Transverse dispersivity, cm | 3^x |
| Initial Volumetric water content | 0.14 |
| Water flow boundary conditions: Top boundary condition | Atmospheric BC |
| Bottom boundary condition | Free drainage |
| Solute boundary conditions: Top and Bottom Boundary condition | Cauchy (Third type) |

^a laboratory data
^b Danilo et al., 2013
^c Siyal et al., 2013
Fig. 1. Transport domain details showing the initial concentrations of Zinc and Nickel respectively.

3 RESULTS AND DISCUSSION

The existing concentration of nickel and zinc in the soil is as shown in Table 1. As India lacks proper guidelines that limit the heavy metal concentration in the soil, the CCME (Canadian Council of Ministers of the Environment) environmental quality guidelines are used to compare the existing contaminant levels (MoEFCC, 2015). As per this, the soil screening levels for nickel and zinc in the industrial area are 50 mg/kg and 360 mg/kg respectively. Comparing to this, it can be observed that the soil is contaminated with nickel up to a depth of 150 cm from the surface whereas the zinc concentration is slightly higher in topsoil.

HYDRUS 2D simulations are used to calculate the concentration profile of heavy metals in the pore water and are shown in Fig 2 and 3. The nickel concentration in the liquid phase is 0.025 mg/cm³ (25 mg/l) in the topsoil and it gradually decreases with respect to time because of the water flux resulted from rainfall. The peak nickel concentration at any depth of the transport domain can be attributed to leaching/desorption of nickel from the soil surface to porewater from the above layers. From Fig 2 it can be observed that the initial pore water concentration was around 0.0085 mg/cm³ (8.5 mg/l) at N2 and reaches a peak value of 0.0139 mg/cm³ (13.9 mg/l) at the end of second year. This might due to the effect of desorption of nickel from the soil along with the addition of nickel from overlying soil pore water. The lower concentration of total nickel in the soil at zone II (Fig 1) has shown reduced initial nickel level in pore water at N2 (50 cm) compared to top surface soil. The nickel concentration in the topsoil acts as a source for the soil layers below to which subsequent peaks are observed at N5 (200 cm), N6 (250 cm) and N7 (300 cm) at different time intervals (Fig 2). The infiltrating rainwater leaches the nickel from the topsoil and carries it to the subsurface soil layers. It can be observed that at the end of 7.5 years, the nickel concentration in the liquid phase will be 0.001 mg/cm³ (1 mg/l) at N7 (300 cm). For drinking water, the permissible limit for nickel as per IS 10500 is 0.02 mg/l. At the end of 7.5 years the porewater at the bottom node of the transport domain carries nearly 50 times higher concentration compared to drinking water standards indicating a high potential of groundwater contamination. Compared to zinc, the total nickel concentration in the soil profile is higher and has increased the risk of contamination. Hence further investigation needs to be carried out to understand the depth and spatial extent of the contamination and accordingly remediation strategies need to be planned to arrest the movement of nickel from reaching the groundwater table.

Fig. 2. Concentration profile for Nickel at different observation nodes.

The redistribution of zinc in the transport domain is given in Fig 4 and 5. The initial liquid phase zinc concentration 0.034 mg/cm³ (33.4 mg/l) at topsoil reaches a concentration of 0.001 mg/cm³ (1 mg/l) by the end of the 25th year. The desirable and the permissible limit for zinc as per IS 10500 drinking water standards is 5mg/l and 15 mg/l respectively. The simulation results show that the liquid phase concentration reaches less than 5 mg/l at 100 cm soil depth and also the zinc concentration is less than drinking water standards at any other depths. The lower concentration of total zinc in soil at zone II and III has reduced its impact on potential groundwater contamination from zinc. The current simulation studies might have resulted in a higher concentration of solutes as it is assumed that the entire transport domain is with uniform soil horizons. However further optimization of the simulated results can be made by considering different soil horizons and kinctecis of adsorption and
desorption of the metals by soil.

Fig. 3. Transport of nickel at i) 0 years ii) 5 years iii) 10 years iv) 15 years v) 20 years.

Fig. 4. Concentration profile for Zinc at different observation nodes.

Fig. 5. Transport of zinc at i) 0 years ii) 5 years iii) 10 years iv) 15 years v) 20 years.

4 CONCLUSIONS

The study helps in understanding the redistribution of contaminants in the vadose zone. From the simulation, it is observed that the nickel concentration in the porewater at exit boundary is 50 times more than prescribed standards leading to high risk of groundwater pollution from nickel than that of zinc. In spite of having a higher concentration in the soil solution, the zinc concentration reaches safer drinking water levels after 100 cm from the top surface. These simulations help in analyzing the extent of contamination vertically and also in arriving immediate remedial plans for both groundwater and soil.

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