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Estimation of Lead (Pb) Flux, Distance of Travel and Break through Time Using Convective Flux Equations: A Case Study of Farmlands around Lead (Pb) Contaminated Goldmine in Zamfara Nigeria

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Authors' contributions

All authors contributed equally in this paper. All authors read and approved the final manuscript.

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Case Study

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ABSTRACT

Estimating the transport and fate of chemicals released into the environment is an interesting and challenging task. The global environment is diverse on the chemical transport and fate scale. This paper applies the mathematics of convection to estimate the extent of lead (Pb) as it travels towards ground water. Highest flux (q_s) value of 9.62 X 10^{-3} cm hr^{-1} was obtained at the initial time of estimation (72 hours) while the lowest q_s value estimated is found to be 1.58 X 10^{-7} when the highest time (438000 hours) was used in the estimation. Break through values ranged from 17822.57-1.08 X 10^{8} hr^{-1} in Dareta North, while it ranges from 11275.5-68592631 hr^{-1} in Dareta South. The results for estimated values of Pb flux, distance of travel and breakthrough time using convective flux equations in the study area suggests that Pb travel through the soil down the groundwater at an increasing flux as this will require immediate measures to curtail this. As the break through time needed for Pb to travel at a distance of 3.46 x 10^{-3} cm hr^{-1} with a q_s value of 3.81 x 10^{-4} cm hr^{-1} through the soil to the ground water (with at distance of 10 m from the ground) after ten years if all things being equal is estimated to be 289080 hr^{-1}.

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1. INTRODUCTION

A number of chemicals that are in the soil solution and in soluble forms are referred to as solutes. The movement of these solutes through soil to groundwater or free water surfaces indicates process leading to the contamination of these resources. In many cases, serious human and health implications are associated with this form of pollution.

In recent years, this problem of groundwater contamination by heavy metals has received much attention. In particular, lead (Pb) is a heavy metal of serious environmental concern. One of the physiological effects of Pb is that it is detrimental to the neurological development of children. Reduction in IQ and other health effects are evident from several case studies [1,2].

Some of the sources of lead are gasoline, paints, antiknock additives in fuel, pigments and stack emissions from some metal industries. Major sources for Pb in ground water are the smelter sites and areas where there has been significant mining activity (as in the case of the study location). Drainage flowing from mine tailings can enter surface water, irrigated soils and groundwater, causing harm to human beings and animals. An understanding of the movement of lead in soils, and its interaction with the soil minerals is important [3].

When a solute (such as Pb) enters a soil matrix (which can be in a soil core, repacked soil column, or agricultural soil in a field) the initial sharp boundary between the resident and displacing solute starts diminishing mainly due to the twin processes of diffusion and dispersion. The transport of a solution through soil matrix consists of three main components: convection, diffusion, and dispersion [4]. Convective flux which happens to be of interest in this work is explained below.

Convective or advective transport of a solution inside a soil matrix is known as a passive movement with flowing soil water. If the transport process has only convective transport without any diffusion, the water and solute move at the same average flow rate. Mathematically, convective transport (J_m) can be expressed as:

$$Jm=qsC \quad (1)$$

In which J_m is the flux density for convective or mass transport ($ML^{-2}T^{-1}$), qs is the volumetric fluid flux density with dimensions of velocity (LT^{-1}), and C is the volume averaged solute concentration (ML^{-3}). The flux density of water can be calculated by the Darcy's equation for a steady state flow of water. The qs is also analogous to θ, where v is the pore water velocity (LT^{-1}) [5].

The resultant pollution of expanse of land and water from artisanal mining of gold in Dareta, northern Nigeria (study location), has placed many people at risk leading to death of several hundreds of children. This paper is written with the aim of using convective equations to estimate Pb flux, distance of travel and breakthrough time in order to estimate time it will take Pb contaminant to pollute ground water in the study area.

2. METHODS

2.1 Study Area

The study was conducted at Dareta village, Anka Local Government Area of Zamfara State in northern Nigeria. Dareta village has been receiving major outbreaks of Pb poisoning since 2010, which is related to artisanal mining processes of Pb rich ore for the extraction of gold [6,5]. Dareta is located on latitude 12°06′30″N and longitude 5°56′00″E, and has an area of 2,746 km² and an estimated population of 142,280 according to the 2006 population and housing census [7]. Farming is one of the major activities of inhabitants of Dareta under rain-fed and irrigation conditions. The crops grown under irrigation are mostly vegetables such as spinach, lettuce, cabbage and onions while arable crops produced are cowpea, millet, sorghum, ground nut. The climate is warm with temperature rising up to 30ºC between March and May. Rainy season starts in late May to September while the cold season known as Harmattan lasts from December to February. The onset of the rains, on the regular, is between mid-March and May, lasting for about six months up to the end of October with an annual average of about 579 mm [8].

2.2 Soil Sampling, Handling and Preparation

Eight soil profile pits were dug to a depth and width of both 1 m in eight different farmlands (two farms per sampling direction). The living perimeter of the village was secured and profile digging proceeded along the four coordinates (North, South, East and West) starting from the first farmland after the last house, on a grid at distances 50 and 100 m. Leaching studies were carried out using free drainage lysimeters with these profile pits. A sunken bed at a depth of 10 cm and 30 cm in length was dug which was ponded 20 litres of water. The results of the leaching studies are not of interest in the current study. The concentration of Pb in soil used in the estimation was determined by Fast Sequential Atomic Absorbtion Spectrophotometer (AAS: Model VARIAN AA240FS) following aqua regia digestion as described by Lim and Jackson [9].

2.3 Estimation of Pb Flux, Distance of Travel and Break through Time through Calculations from Convective Flux Equations

Convective equations were used to estimate solute flux density of soil profiles for 72 hours (3 days), 8,760 hours (1 year), 43,800 hours (5 years), 87,600 (10 years), 175200 hours (20 years) and 438000 hours (50 years) in Dareta village that is to predict the flux of solute and make projections of the time it will reach some distant points in the village from the polluted sites.

$$J_m = q_s C \qquad (2)$$

In which

J_m = convective (mass flow)

q_s = flow per unit cross sectional

C is the mass per unit volume of solution (concentration of Pb contaminant)

In;

C = 12.43 mg l^{-1}

q_s =?

To determine flux we use;

$$q_s = Q/_A \qquad (3)$$

Q = volumetric flow rate across the lysimeter

A = cross sectional area

$$\text{But } Q = {}^{v}/_{t} \qquad (4)$$

Where

$$v = 20 \text{ litre} = 20000 \text{ cm}^3$$
$$t = 3\ days = 72\ hours$$
$$Q = {}^{20000}/_{72}$$
$$= 277.78\ cm^3\ hr^{-1}$$

To determine cross sectional area (A)

$$A = l \times b$$

l = 30 *cm* (length of ponding surface)

b = 10 *cm* (breadth of ponding surface)

$$A = 30 \times 10$$

$$= 300\ cm^2$$

$$q_s = {}^{277.78}/_{300}$$

$$9.26 \times 10^{-1} \text{ cm } hr^{-1}$$

Therefore;

$$J_m = 9.26 \times 10^{-1} \times 12.43$$
$$= 11.51\ mg \text{ cm } hr^{-1}$$

The distance of travel per unit term of solute is given by;

$$V = {}^{q_s}/_{\theta} \qquad (5)$$

In which is moisture content and other terms as previously defined.

Where;

$$q_s = 9.26 \times 10^{-1}\ cm\ hr^{-1}$$
$$\theta = 0.22$$
$$V = {}^{9.26 \times 10^{-1}}/_{0.22}$$

$$= 4.21\ cm\ hr^{-1}$$

To estimate the distance of travel of Pb pollutant from the soil to the water table through the water table we use;

$$t_r = \frac{l\theta}{qs} \quad (6)$$

In which *l* is the depth of water table in Dareta village which was determined to be = 1000 cm and other terms as previously defined.

$$t_r = \frac{1000\times0.22}{9.26\times10^{-1}}$$
$$= 237.6\ hr^{-1}$$

3. RESULTS AND DISCUSSION

3.1 Estimated Values of Pb Flux, Distance of Travel and Break through Time Using Convective Flux Equations in Dareta Village

The results for estimated values of Pb flux, distance of travel and break through time using convective flux equations in Dareta North, South, East and West are presented in Tables 1-4.

Volumetric flow rate (Q), Pb flux (q_s), convective flux (J_m) and distance of travel (V) all decrease with increase in time. Even though the same values of Q and q_s were used in estimating the t_r for all the sampling directions. This is because values such as volume of V, t, A, L used in estimating Q and q_s across the sampling direction were the same as previously mentioned in chapter three. Highest J_m values obtained was after three days of estimation with Dareta North having a J_m of 1.15×10^1 cm hr^{-1} while Dareta South recorded 1.17×10^1 cm hr^{-1}. Distance of travel (V) decrease with increase in time across the sampling directions. This decrease which is not rapid may cause all the soil layers in that location to be contaminated with before reaching the groundwater. Dareta East and West recorded lowest V values of 8.10×10^{-4} cm hr^{-1} and 9.22×10^{-4} cm hr^{-1} respectively when an estimated time of 14,600 days (40 days) was used. Break through time (t_r) values estimated unlike other values increases with increase in t across the sampling directions because of decrease in volumetric flow rate (Q) and flux (qs). Its estimated as the amount of time it will take the Pb contaminant to reach ground water. Higher tr values are required for lesser Q and qs values. Break through values ranged from 237.6-1445400 hr^{-1} in Dareta North while it was found to range from 216-1084050 hr^{-1} in Dareta West. Chemicals in the soil undergo two fates based on their duration whether on a short-term or a long-term disposition to another chemical or storage [10]. The time scale of the calculations is important in determining how we deal with the problem or how we set up our solution. If Pb contaminant is in groundwater, the media are soil and water. The short-term fate will be that the Pb will be primarily adsorbed to the soil. Soil organic matter and high surface area clays tend to be the strongest absorbents of some contaminants although they are little for Pb contaminants while oxide coatings on soil particles strongly adsorb others [11]. The long-term fate is that it will desorbs and the Pb-laden water may be consumed when sourced from natural groundwater sources such as wells, streams, rivers, bore holes.

Table 1. Estimated solute flux, distance of travel and break through time from convective equations in Dareta North

D	*hr*	*Q* (cm hr^{-1})	q_s (cm hr^{-1})	J_m (cm hr^{-1})	*V* (cm hr^{-1})	t_r (hr^{-1})
3	72	2.77×10^2	9.26×10^{-1}	1.15×10^1	0.42×10^1	237.6
30	720	2.77×10^1	9.26×10^{-2}	0.11×10^1	4.21×10^{-1}	2376
365	8760	0.22×10^1	7.61×10^{-3}	9.46×10^{-2}	3.46×10^{-2}	28908
1825	43800	4.57×10^{-1}	1.52×10^{-3}	1.89×10^{-2}	6.92×10^{-3}	144540
3650	87600	2.28×10^{-1}	7.61×10^{-4}	9.46×10^{-3}	3.46×10^{-3}	289080
7300	175200	1.14×10^{-1}	3.81×10^{-4}	4.73×10^{-3}	1.73×10^{-3}	578160
14600	438000	4.57×10^{-2}	1.52×10^{-4}	1.89×10^{-3}	6.92×10^{-4}	1445400

D = days, hr = hour = Q = volumetric flow rate across the lysimeter, q_s = flow per unit cross sectional area per unit time, J_m = convective flow (mass flow), V = distance of travel, t_r = break through time

Table 2. Estimated solute flux, distance of travel and break through time from convective equations in Dareta South

D	*hr*	*Q* (cm hr⁻¹)	q_s (cm hr⁻¹)	J_m (cm hr⁻¹)	*V* (cm hr⁻¹)	t_r (hr⁻¹)
3	72	2.77×10^{2}	9.26×10^{-1}	1.17×10^{1}	0.44×10^{1}	226.8
30	720	2.77×10^{1}	9.26×10^{-2}	0.11×10^{1}	4.75×10^{-1}	2106.0
365	8760	0.22×10^{1}	7.61×10^{-3}	9.18×10^{-2}	3.86×10^{-2}	25885.8
1825	43800	4.57×10^{-1}	1.52×10^{-3}	1.72×10^{-2}	7.61×10^{-3}	131400
3650	87600	2.28×10^{-1}	7.61×10^{-4}	7.83×10^{-3}	4.09×10^{-3}	244404
7300	175200	1.14×10^{-1}	3.81×10^{-4}	3.88×10^{-3}	2.15×10^{-3}	465156
14600	438000	4.57×10^{-2}	1.52×10^{-4}	1.39×10^{-3}	7.69×10^{-4}	1300860

D = days, hr = hour = Q = volumetric flow rate across the lysimeter, q_s = flow per unit cross sectional area per unit time, J_m = convective flow (mass flow), V = distance of travel, t_r = break through time.

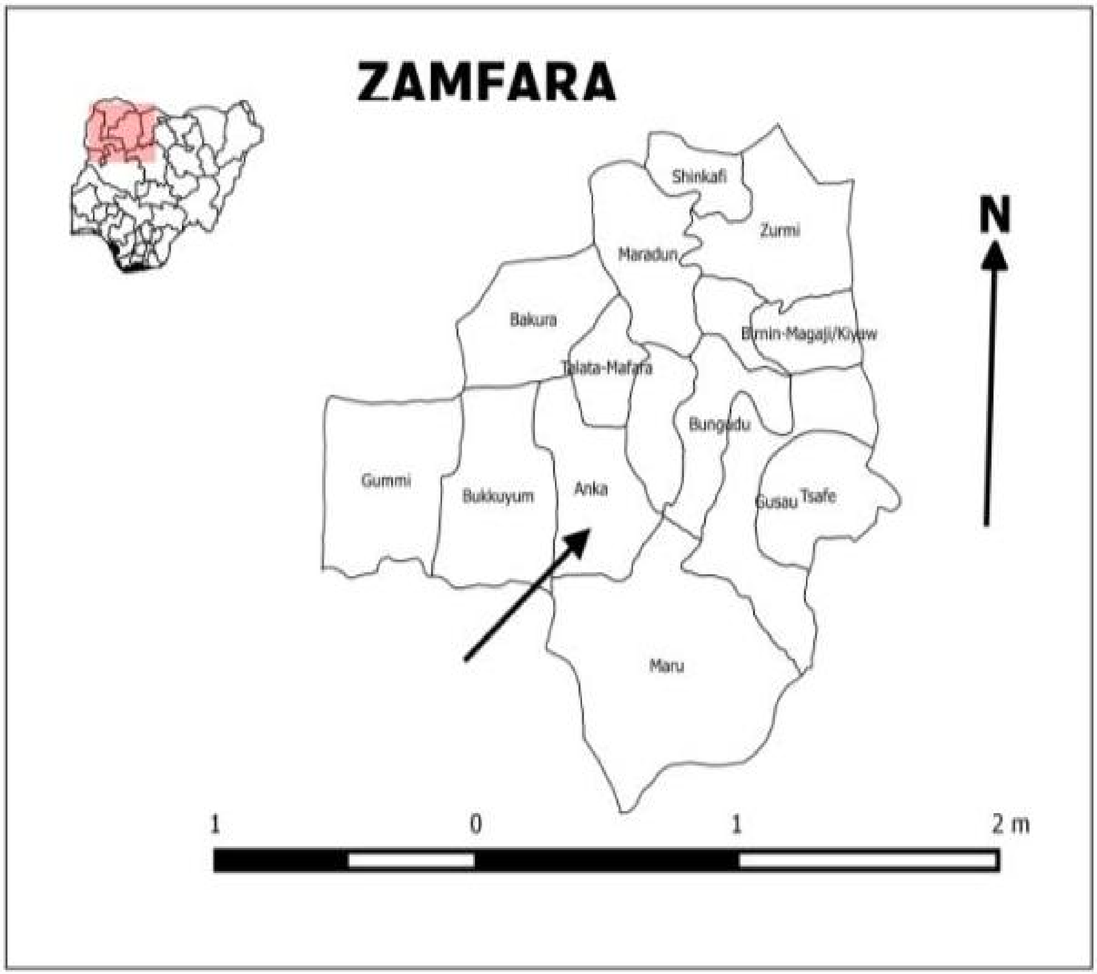

Fig. 1. Map of Zamfara, showing the location of Dareta Village, where soils for the study were obtained

Table 3. Estimated solute flux, distance of travel and break through time from convective equations in Dareta East

D	*hr*	*Q* (cm hr^{-1})	q_s (cm hr^{-1})	J_m (cm hr^{-1})	*V* (cm hr^{-1})	t_r (hr^{-1})
3	72	2.77×10^{2}	9.26×10^{-1}	1.06×10^{1}	0.43×10^{1}	233.3
30	720	2.77×10^{1}	9.26×10^{-2}	0.10×10^{1}	4.70×10^{-1}	2127.6
365	8760	0.22×10^{1}	7.61×10^{-3}	8.05×10^{-2}	4.07×10^{-2}	24571.8
1825	43800	4.57×10^{-1}	1.52×10^{-3}	3.72×10^{-2}	7.61×10^{-3}	131400
3650	87600	2.28×10^{-1}	7.61×10^{-4}	7.43×10^{-3}	4.32×10^{-3}	231264
7300	175200	1.14×10^{-1}	3.81×10^{-4}	3.78×10^{-3}	2.15×10^{-3}	465156
14600	438000	4.57×10^{-2}	1.52×10^{-4}	1.32×10^{-3}	8.10×10^{-4}	1235160

D = days, hr = hour = Q = volumetric flow rate across the lysimeter, q_s = flow per unit cross sectional area per unit time, J_m = convective flow (mass flow), V = distance of travel, t_r = break through time.

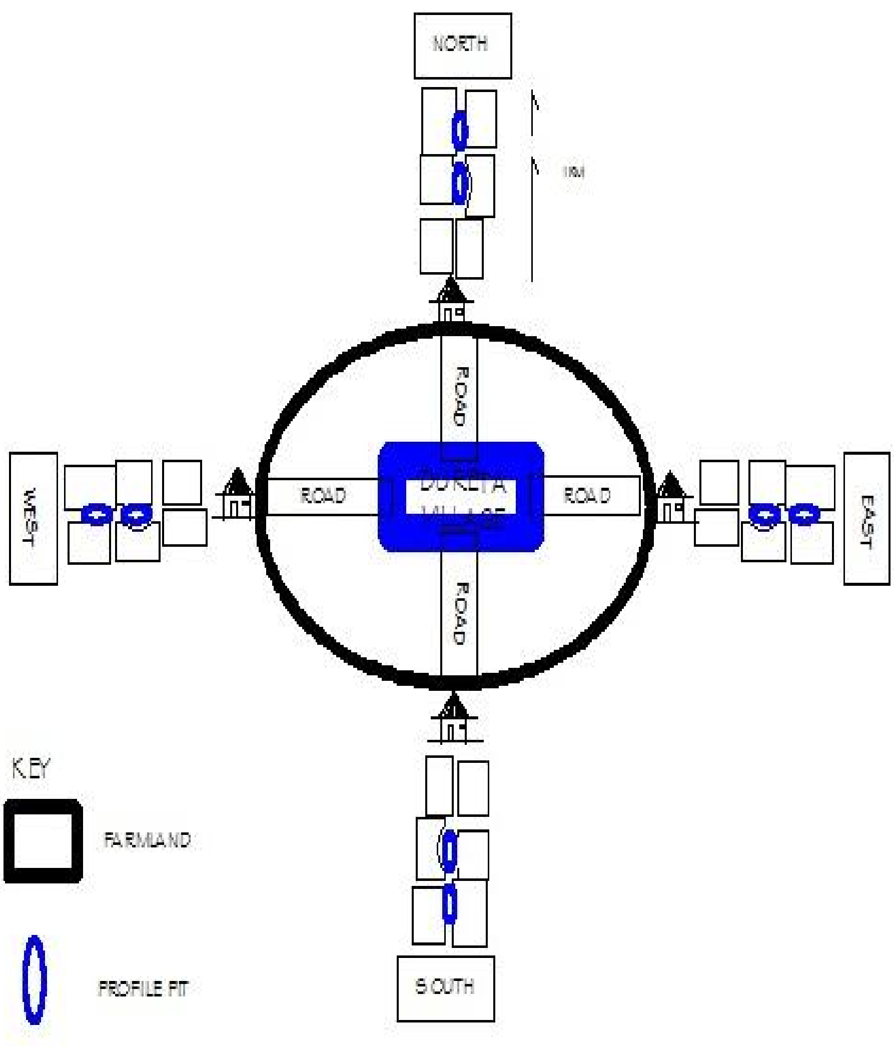

Fig. 2. Field layout of the sampling points in the study location with respect to the last house in Dareta village (Adopted from Mohammed and Abdu, 2013)

Table 4. Estimated solute flux, distance of travel and break through time from convective equations in Dareta West

D	*hr*	*Q* (cm hr^{-1})	q_s (cm hr^{-1})	J_m (cm hr^{-1})	*V* (cm hr^{-1})	t_r (hr^{-1})
3	72	2.77×10^{2}	9.26×10^{-1}	1.10×10^{1}	0.46×10^{1}	216.0
30	720	2.77×10^{1}	9.26×10^{-2}	0.19×10^{1}	4.68×10^{-1}	2138.4
365	8760	0.22×10^{1}	7.61×10^{-3}	8.11×10^{-2}	4.05×10^{-2}	24703.2
1825	43800	4.57×10^{-1}	1.52×10^{-3}	1.57×10^{-2}	7.15×10^{-3}	139941
3650	87600	2.28×10^{-1}	7.61×10^{-4}	8.42×10^{-3}	3.88×10^{-3}	257544
7300	175200	1.14×10^{-1}	3.81×10^{-4}	3.56×10^{-3}	2.47×10^{-3}	404712
14600	438000	4.57×10^{-2}	1.52×10^{-4}	1.41×10^{-3}	9.22×10^{-4}	1084050

D = days, hr = hour = Q = volumetric flow rate across the lysimeter, q_s = flow per unit cross sectional area per unit time, J_m = convective flow (mass flow), V = distance of travel, t_r = break through time.

4. CONCLUSION

The results for estimated values of Pb flux (q_s), distance of travel and break through time using convective flux equations in Dareta village shows that q_s values were the same across the estimated times chosen in all sampling directions because a constant value of Q and t were used all through during the estimation. Highest q_s value of 9.62 X 10^{-3} cm hr^{-1} was obtained at the initial time of estimation (72 hours) while the lowest q_s value estimated is found to be 1.58 X 10^{-7} cm hr^{-1} when the highest time (438000 hours) was used in the estimation. Break through values ranged from 17822.57-1.08 X 10^{8} hr^{-1} in Dareta North, while it ranges from 11275.5-68592631 hr^{-1} in Dareta South. These estimated results suggests that the rate at which Pb travel through the soil down the groundwater and that immediate measures have to be taken to curtail this.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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