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Modelling Radionuclides Transport in a Groundwater System Around a Goldmine Site in Burkina Faso

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Abstract: ***Radionuclides transport in groundwater system is described using a numerical method in MatLab. The activity concentration and annual committed effective dose (ACED) to the public from consumption of the natural radionuclides ^{238}U and ^{232}Th were determined. The maximum activity concentrations were around 0.3 Bq/L, and 0.08 Bq/L for ^{238}U and ^{232}Th respectively. The activity concentration tends to be neglected at 1500 m for ^{238}U and 1000 m for ^{232}Th. from the discharged point. The corresponding annual committed effective dose estimated was 0.022 mSv/y. The results obtained for this study are far below the recommended levels of 10.0 Bq.L^{-1} and 1.0 Bq.L^{-1} for ^{238}U and ^{232}Th respectively for drinking water established by the WHO and 1 mSv per year dose limit recommended by the ICRP for public radiation exposure.***

Keywords: **Modelling, Groundwater, Activity Concentration, Committed Effective Dose, Uranium, Thorium.**

1. Introduction

Groundwater is water that occurs in pores and fractures in soil and rocks below the watertable. Groundwater flow and transport analysis have been an important research topic in the last three decades [1]. This is because, it is one of the most important pathway for transport of radioactive contaminations in the soil. Unfortunately, this type of contamination is difficult to sample and monitor and it requires great dependence on models to predict the transport and fate as well as the variation of concentration along this pathway. Water is vital and, concurrently, one of the most important natural resources. About 70% of the Earth's surface is covered with water, which is estimated at a volume of approximately 1.4 billion km^3. However, most of it is salty, and only around 2.5% of the global water resources (about 35 million km^3) consists of freshwater [2]. Then, Groundwater is the most important and highly used resource; however, its quality can be endangered. It is known that radionuclides could accumulate during mining and mineral ore processing and reach into water bodies, and thus contribute to the radiation dose received by the public who consume this water. There is the need for an assessment of human exposure to radiation. Therefore, it is necessary to examine naturally occurring radioactivity in the environment, especially the occurrence of natural radioactivity in groundwater [2].

The objective of the study was to predict radionuclide concentration and Committed Effective Dose in a groundwater system around some goldmine site in Burkina Faso at various distances from the site. This was achieved by determining the concentration of ^{238}U and ^{232}Th using a mathematical model with numerical method especially Finite Differential Method in MatLab.

2. Material and Methodology

2.1. Conceptual Model

The level of radioactivity in groundwater system may increase as a result of possible migration of radionuclides to groundwater due to the processing activities of the mines.[3] As the groundwater flows, the contaminant is carried out from boreholes and wells because most of the time as the groundwater serves as the major source of water for drinking, household purposes and irrigation.

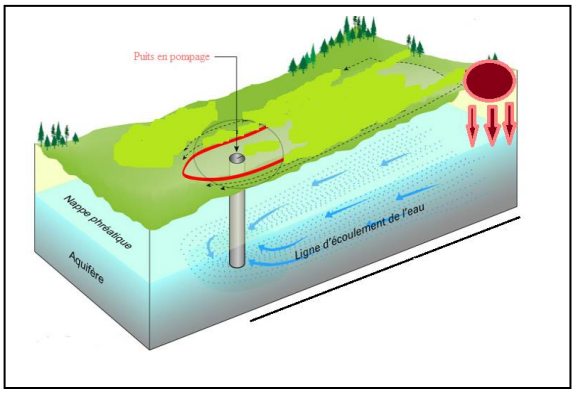

Figure1: Goundwater system transport

2.2. Mathematical Model

2.2.1. Derivation of the governing equation

In general, the flow and contaminant transport equations are developed from the fundamental principle, namely; the conservation of fluid and dissolved mass. The general conservation equation can be expressed as [4]

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Rate of mass input –rate of mass output+rate of mass production/consumption= rate of mass accumulation

The differential equations describing the transport of contaminant in groundwater are also developed from conservation statement. Let the flux of a particular dissolved constituent into and out of a volume element of porous medium be represented by **J.**

The continuity equation has the following form [1].

$$\frac{\partial}{\partial x}(J_x)+\frac{\partial}{\partial y}(J_y)+\frac{\partial}{\partial z}(J_z)\pm r=\frac{d(\varepsilon C)}{dt} \quad (1)$$

WhereJ_k: flux of a particular dissolved constituent in a volume element of a porous medium in the r diection (k=x,y ,z); ε: Porosity ; r: source term within the volume ; C: mass concentration.

The mass Transport of a dissolved species is controlled by three processes: diffusion, dispersion, and advection.[4] Mathematically the advective flux of a contaminant is described by the first term at the right in (2) and the dispersion component is described by Fick's Law represented by the second term.

$$J_k=V_k\varepsilon C-\varepsilon D_k\frac{\partial C}{\partial x}, \qquad k=x, y\ z \quad (2)$$

Where, D_k is the dispersion coefficient in the k direction *(k= x,y,z)*

Substituting (2) into (1) in gives:

$$-\left[\begin{array}{l}\frac{\partial}{\partial x}\left(V_x\varepsilon C-\varepsilon D_x\frac{\partial C}{\partial x}\right)+\\ \frac{\partial}{\partial y}\left(V_y\varepsilon C-\varepsilon D_y\frac{\partial C}{\partial y}\right)+\\ \frac{\partial}{\partial y}\left(V_z\varepsilon C-\varepsilon D_z\frac{\partial C}{\partial z}\right)\end{array}\right]\pm r=\frac{\partial}{\partial t}(\varepsilon C) \quad (3)$$

2.2.2. Assumptions made in the Model

In this model, equation for transport of radionuclides in groundwater was used [. The following assumptions were made; The contaminant concentration at initial time is neglected (i.e., C(x, 0) = 0); The aquifer is homogenous and isotropic, i.e., K is constant in all directions; The groundwater flow characteristics (e.g. seepage velocity, groundwater depth, groundwater width, etc.) do not change significantly with distance and time; Porosity and dispersion coefficients are constant; Adsorption is a reversible process at equilibrium, represented by a linear isotherm. [5]

For radionuclide decay and the mass transport accompagnied by sorption that is described in terms of a simple linear isotherm, the source term is given respectively by :

$$r=d/dt(\varepsilon C)=-\lambda\varepsilon C \text{ and } -r=\rho\frac{\partial S}{\partial t}=\rho K_d\frac{\partial C}{\partial t} \quad (4)$$

Where, λ is the radionuclide decay constant related to the half-life for decay ; ρ is the bulk density of the medium ; S is the quantity of mass sorbed on the surface, and ; K_d is the distribution coefficient.

Taking account of the assumptions made and Substituting (4) into (3) and rearranging gives a resulting constituent transport equation in 1-D for a continuous release as:

$$R\frac{\partial C}{\partial t}+V_x\frac{\partial C}{\partial x}=D_x\frac{\partial^2 C}{\partial x^2}-\lambda RC \quad (5)$$

V_x - mean groundwater velocity or seepage velocity in x directions (m/s) ; x - Longitudinal direction (m) ;

D_x-dispersion coefficients in x directions (m^2/s) ; λ - Radionuclide decay constant (s^{-1}) ;

t-time(s);

R-Retardation factor is given by

$$R=1+\frac{\rho K_d}{\varepsilon} \quad (6)$$

The components of the formula (6) are defined before.

2.2.3. Initial and boundary Conditions

Three types of boundary conditions are generally associated with the contaminant-transport equation: the Dirichlet (or first-type), Neumann (or second-type), and Cauchy (or third-type) boundary conditions.

The following initial and boundary conditions are applied for this study,

$$C(x,t)_{t=0}=0 \qquad 0\le x\le L$$
$$C(0,t)=C_0 \qquad 0<t_0\le t \quad (7)$$

2.2.4. Discretization of the differential equation

The partial differential equation in (5) above was solved by employing finite difference method to obtain a solution. The finite difference method was used because it allows to approximate the derivatives appearing in the equation by a set of values of the function at a selected number of points. The time and distance were discretized using Euler's forward in time and centered difference in space, a matrix was then generated to determine the concentration of natural radionuclides in groundwater system. Distance and time axes were discretized into intervals of Δx, and Δt respectively. A mesh of uniformly spaced grid-lines were introduced as

$$x_i=i\Delta x;\ \ t^n=n\Delta t\ ;\ i=1,2,3...I\ ;\ \ n=1,2,3...N$$

Where, *I* denote the total number of spatial grid-spacing and *N* denotes the total number of temporal grid-spacing. The figure 2 shows the model of the domain discretization.

Now, approximating the derivatives using Euler's forward difference in time and centered difference in space at point O, the following is obtained

$$\frac{\partial C}{\partial t}=\frac{C_i^{n+1}-C_i^n}{\Delta t} \quad (8)$$

$$\frac{\partial C}{\partial x}=\frac{C_{i+1}^n-C_{i-1}^n}{\Delta x} \quad (9)$$

$$\frac{\partial^2 C}{\partial x^2}=\frac{C_{i+1}^n-2C_i^n+C_{i-1}^n}{\Delta x^2} \quad (10)$$

Inserting (8), (9) and (10) into (5) gives

$$R.\frac{C_i^{n+1}-C_i^n}{\Delta t}+V_x.\frac{C_{i+1}^n-C_{i-1}^n}{\Delta x}=D_x.\frac{C_{i+1}^n-2C_i^n+C_{i-1}^n}{\Delta x^2}-R\lambda C_i^n \quad (11)$$

Multiplying through by Δt, dividing by R and rearranging gives,

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$$C_i^{n+1} = \begin{bmatrix} (1-\lambda\Delta t - \frac{2D_x.\Delta t}{R.\Delta x^2})C_i^n + \\ (-\frac{V_x.\Delta t}{R.\Delta x} + \frac{D_x.\Delta t}{R.\Delta x^2})C_{i+1}^n + \\ (\frac{V_x.\Delta t}{R.\Delta x} + \frac{D_x.\Delta t}{R.\Delta x^2})C_{i-1}^n \end{bmatrix} \quad (12)$$

Equation (11) can be rewritten simply:

$$C_i^{n+1} = AC_{i-1}^n + BC_i^n + DC_{i+1}^n \quad (13)$$

Where,

$$A = \frac{V_x.\Delta t}{R.\Delta x} + \frac{D_x.\Delta t}{R.\Delta x^2} \quad ; \quad B = 1 - \lambda\Delta t - \frac{2D_x.\Delta t}{R.\Delta x^2}$$ And,

$$D = -\frac{V_x.\Delta t}{R.\Delta x} + \frac{D_x.\Delta t}{R.\Delta x^2}$$

Applying the initial and boundary conditions, the following matrix form is obtained

$$\begin{pmatrix} C_1^{n+1} \\ C_2^{n+1} \\ \vdots \\ \vdots \\ \vdots \\ C_{i-1}^{n+1} \\ C_i^{n+1} \end{pmatrix} = \begin{bmatrix} B & D & 0 & 0 & \cdots & \cdots & 0 & 0 \\ A & B & D & 0 & \ddots & \ddots & \ddots & 0 \\ 0 & A & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & D & 0 \\ 0 & \ddots & \ddots & \ddots & 0 & A & B & D \\ 0 & 0 & \cdots & \cdots & 0 & 0 & A & B \end{bmatrix} \begin{bmatrix} C_1^n \\ C_2^n \\ \vdots \\ \vdots \\ \vdots \\ C_{i-1}^n \\ C_i^n \end{bmatrix} + \begin{pmatrix} A*C_0^n \\ 0 \\ 0 \\ \vdots \\ \vdots \\ 0 \\ 0 \\ D*C_{i+1}^n \end{pmatrix} \quad (14)$$

Or simply

$$C^{n+1} = MC^n + V \quad (15)$$

This matrix system is implemented in MathLab code to obtain the activity concentration of radionuclides of interest

2.3. Annual committed effective Dose estimation

The concentrations of radionuclides were used to estimate the Annual committed effective Dose.

The ingestion doses for infants and adults are calculated using the following general equation,

$$E_{ing,p} = C_{p,i} H_p DF_{ing} \quad (16)$$

Where ; $E_{ing,p}$ is the annual effective dose from consumption of nuclide (Sv/y) ; $C_{p,i}$ is the concentration of radionuclide *i* in drinking water at the time of consumption (Bq/m^3) ; H_p is the consumption rate for drinking water (m^3/y) ; DF_{ing} is the dose coefficient for ingestion of radionuclide *i* (Sv/Bq).

The dose coefficient values given are those recommended in the BSS for all unspecified compounds for the purpose of calculating doses [6], [9].

3. Results and Discussions

3.1. Simulation of Uranium-238

Figures 2 and 3 show the results from the simulation of Uranium-238 with respect to time and distance

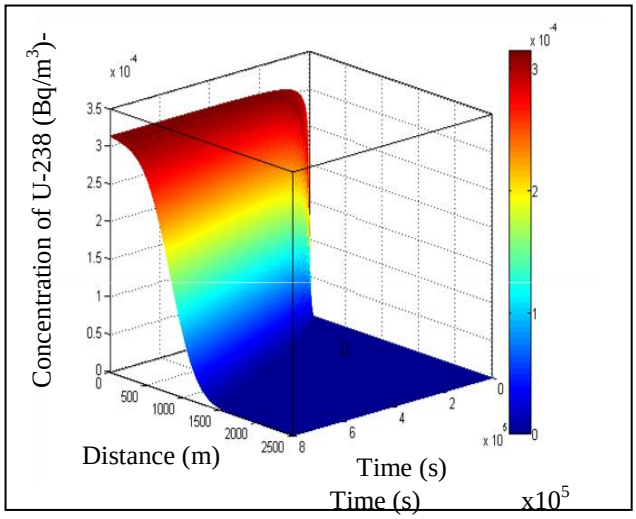

Figure 2: 3D Plot of Variation of the concentration of Uranium-238 with time and at various distances from discharge point

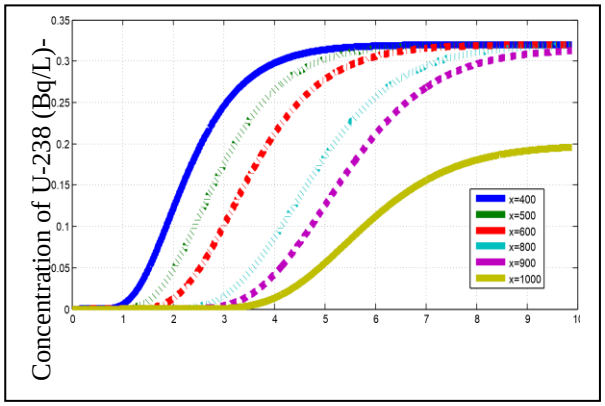

Figure 3: 2D Plot of Variation of the concentration of Uranium-238 with time and at various distances from discharge point

The results indicate that the concentration of Uranium-238 is accumulated at the discharge point and it decreases when the distance increases (Fig.2). The concentration becomes very low at 1500 m beyond the release point. Also, at various distances from the release point, the concentration increases rapidly with time after the beginning of the release and becomes constant after a certain time. (Fig.3). It reaches a maximum of 0.3 Bq/L for a distance less than 900 m and it decreases to be neglected at 1500m and beyond from the release point. This could mean that the wells and boreholes which supplying people as drinking water should be beyond 1500 m (Fig.2) from the mining site to minimise contamination of people through drinking water with Uranium-238 in case of a release due to the mining activities.

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3.2. Simulation of Thorium-232

The variation of ^{232}Th concentration with time and distance from the discharge point is illustrated in Figures 4 and 5, which are 3D et 2D plots respectively

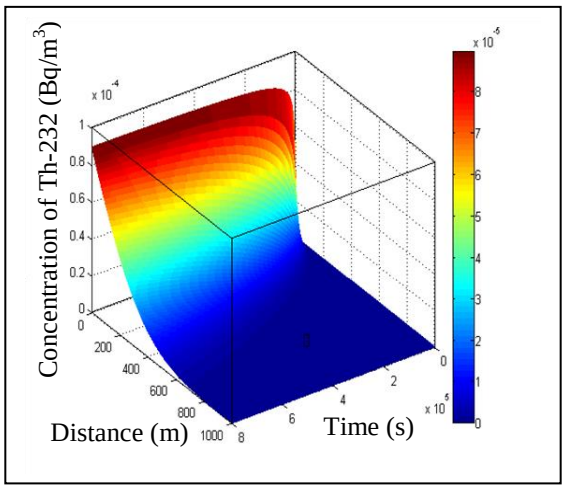

Figure 4: 3D Plot of Variation of the concentration of Thorium-232 with time and at various distances from discharge point

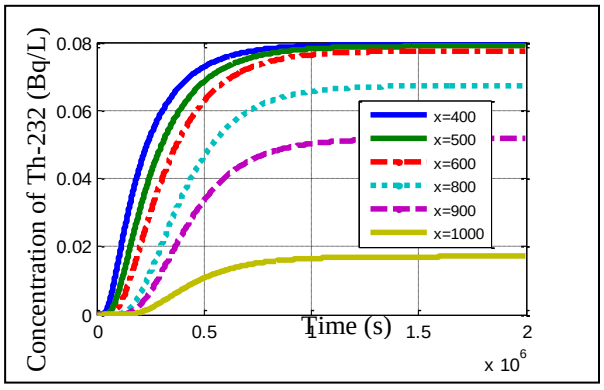

Figure 5: 2D Plot of Variation of the concentration of Thorium-232 with time and at various distances from discharge point

The results from Thorium-232 simulation are similar to the case of Uranium-238 such, the concentration is accumulated at the discharge point and decreases when the distance increases (Fig.4). However, the concentration becomes low at 1000 m beyond the release point compared to Uranium-238 which is very low at 1500 m beyond the release point. Also. At various distances from the release point, the concentration increases rapidly with time after the beginning of release and becomes constant after a certain time (Fig.5). For Thorium-232, the concentration reaches to a maximum of 0.08 Bq/L for a distance less than 600 m and it decreases to be neglected at 1000m and beyond from the release point.. So, for Thorium-232, wells and boreholes which supplying people drinking water should be beyond 1000 m from the mining site to minimise the ingestion of Thorium-232 by people through drinking water.

3.3. Annual Committed Effective Dose

The average activity concentrations were 0.3 Bq/L and 0.08 Bq/L. The corresponding committed effective doses of 0.0096 mSv/y and 0.013 mSv/y were obtained for ^{238}U and ^{232}Th respectively.. The total Dose estimated was 0.022 mSv/y. This value is far below 1 mSv per year dose limit recommended by the ICRP for public radiation exposure.[7], .[8]

4. Conclusion

This study described the use of a mathematical model to simulate transport of Natural Radionuclides in a groundwater system. The simulation allowed the determination of the concentration of the radionuclides from the release point to the receptor location. The activity concentrations were 0.3 Bq/L and 0.08 Bq/L obtained for ^{238}U and ^{232}Th respectively. The total committed effective Dose estimated was 0.022 mSv/y. These values are below the recommended levels of 10.0 Bq.L^{-1} and 1.0 Bq.L^{-1} for ^{238}U and ^{232}Th respectively for drinking water established by the WHO [10]. and 1 mSv per year dose limit recommended by the ICRP for public radiation exposure.
.The results from this work indicate insignificant levels of the natural radionuclides, implying that there is no significant radiological hazard due to NORMS to the communities who are drinking the water from boreholes and wells in this area.

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