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Groundwater Flow Pattern as it Affects theTrend of Heavy Metal Concentration

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ABSTRACT
This study investigated heavy metal transport in soil-groundwater media using mathematical modelling. Initial heavy metal release onto the soil surface was modelled over time, analysing migration patterns and concentration variations across vertical and horizontal domains up to 100 m. Results indicate significant vertical and horizontal migration of the heavy metal from the initial release point. While surface concentrations remained relatively stable over the simulated period (ranging from 1.0120 mg/l to 1.01598 mg/l), concentrations at a depth of 100 me showed a pronounced increase over time, rising from 0.000782 mg/l after one year to 0.09383 mg/l after ten years. At 100 m depth, the heavy metal concentration increased by 99.17% from one to ten years, and 81.12% from five years to ten years. This suggests that while minimal change occurred near the surface, a significant downward transport occurred, with concentrations increasing considerably with depth and time. Sorption mechanisms and hydrodynamic dispersion are identified as factors that influence the transport of the heavy metal contaminant in the media. Changes in concentration along the horizontal direction is smaller compare to the vertical direction. Simulated concentrations at depths from 60 m down are generally low, signifying aquifer zone with quality water suitable for drinking. Ultimately, this model approach offers a valuable insight into heavy metal transport mechanisms and potential accumulation within soil and groundwater storage system.

KEYWORDS: *Modelling, Heavy Metal, Trend, Soil, Groundwater*

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I. INTRODUCTION

Groundwater is the primary source of water for household consumption, industrial activities, and agriculture. Availability of groundwater resource and its sustainability is critical globally. This is because 2.5 billion of the global population depend solely on groundwater to meet their basic daily water needs, with millions of farmers relying on it to sustain food supply (UNESCO, 2012). Groundwater also supports the basic flow of rivers and maintains the aquatic ecosystems. However, climate change and natural variability in water distribution and occurrence threaten the sustainable development of water resources by stressing both the quality and quantity of freshwater from rivers, lakes, groundwater, soil moisture, and ice around the world (Namitha et al., 2019; Aghlmand&Abbasi, 2019).

The conservation and management of groundwater resources are critical challenges for meeting the increasing water demand for agricultural, industrial, and domestic uses. Over-exploitation leads to the depletion of aquifer systems and causes environmental issues such as land subsidence, deterioration of water quality, and saltwater intrusion in coastal areas (Ujile&Owhor, 2018). The utilization of groundwater increases annually, often surpassing the use of surface water (Prakash, 2018). Additionally, the uncertainty over groundwater availability and replenishment rates presents significant challenges in their effective management and reduce their ability to serve as buffer to surface water scarcity, especially during droughts (Khalili et al., 2016; Pathak et al., 2018). The over-exploitation and contamination of water resources have further impacted the environment, affecting ecosystems and human health.

Rainfall contributes to the challenges of groundwater management as low rainfall, in addition to continuous extraction of groundwater resources, can significantly affect the quality and quantity of groundwater. A decline in groundwater levels is a clear indication of water scarcity (Pathak et al., 2018). For example, it was estimated that about 60 percent of groundwater could decline within the next decades. (WWAP, 2015). Therefore, sustainable management of groundwater resources necessitates judicious use and effective policies. Public awareness about threats to water resources and surrounding ecosystems is essential to reduce challenges. Policy decisions regarding water management are necessary to promote responsible use and conservation of water.

Various techniques are involved in protecting groundwater from contamination. Theses could range from identifying pollution sources, treating polluted water, and implementing regulations to prevent further pollution. Continuous monitoring and assessment of groundwater quality are also vital to ensure the safety and sustainability of water supplies. Quantification of groundwater can be achieved through both indirect and direct methods using aerial, surface, and sub-surface techniques. Surface methods include electrical resistivity surveying, vertical electrical sounding, gamma-ray logging, and seismic refraction surveying, which are used to identify groundwater availability and quality. On the other hand, sub-surface techniques involve tracer tests and geophysical logging. Aerial techniques utilize remote sensing methods such as photo geology, Landsat/IRS imagery, infrared imagery, and electromagnetic methods to facilitate groundwater management (Prakash, 2018).

Other important tools and approaches that can be employed to estimate groundwater contaminants is modelling through mathematical approach.Groundwater modelling is crucial tool for both quantification and prediction of contaminant level in soil and groundwater media. Mathematical models enable simulation and prediction of present and future aquifer behaviour,as well contaminant levels (Koohestani et al., 2013). Groundwater models play a vital role in the development, assessment and management of groundwater resources. Different types of models have been used for evaluation of groundwater contaminants and flow analysis. The models could range from conceptual models to analytical and numerical models.

Studies have utilised mathematical models to study the behaviour and pattern of heavy metals and other contaminants in both soil and water (Koohestani et al., 2013; Wu et al., 2024), while other studies use models to predict the concentration of heavy metal migration into soil, from a pollution source (Zeng et al., 2023; Ying et al., 2024). In this study, the advection-diffusion equation was utilised tomodel the trend of heavy metal in soil-groundwater media.

II. MATERIALS AND METHODS

This study utilised mathematical model to simulate the transport of heavy metal contaminant into soil-groundwater media.2-dimensional advection-diffusion equation was used.The initial heavy metal concentration on the soil surface is 5 mg/l, and migrated down across the depth and lateral distance up to 100 metersintothe soil-groundwater media. The concentration of the heavy metal at any point in the soil-groundwater media was predicted by the model from its initial concentration after 1 year, 5 years and 10 years. The 2-dimensional advection-diffusion equation is stated in Equation (1).

$$\frac{\partial C}{\partial t} = -D_x \frac{\partial^2 C}{\partial x^2} - D_z \frac{\partial^2 C}{\partial z^2} - v_x \frac{\partial C}{\partial x} - v_z \frac{\partial C}{\partial z} \quad (1)$$

where:

C = Concentration of contaminants
t = Duration of contaminant transport (day)
x, z = Direction of transport in x- and z-directions along soil depth (m)
D_x, D_z = Diffusion coefficient in x- and z-directions (m^2/day)
v_x, v_z = Diffusion coefficient (m^2/day)

Boundary conditions:

$$t = 0 \quad 0 < X < \infty; \quad C = 0 \quad (2)$$
$$t > 0 \quad X = \infty; \quad C = 0 \quad (3)$$
$$t > 0 \quad X = 0; \quad C = C_o \quad (4)$$

The following assumptions were considered for modelling of the transport modelling of the heavy metals in soil media:

i. Heavy metal decay in soil is negligible.
ii. There is no re-pollution of heavy metal in the soil.

iii. Seepage velocity is negligible in horizontal direction (x-direction).
iv. The diffusion coefficient over the period is constant.
v. The seepage velocity of heavy metal into the soil is constant.

Therefore, the analytical solution to Equation (1), after applying the boundary conditions and the assumptions, is given by Equation (5).

$$C(x,z,t) = \frac{C_o}{2}\left\{erfc\left[\frac{z+x\sqrt{D_x/D_z}-v_z t}{2\sqrt{D_z\left[1+\left(D_x/D_z\right)^2\right]t}}\right] + erfc\left[\frac{z+x\sqrt{D_x/D_z}+v_z t}{2\sqrt{D_z\left[1+\left(D_x/D_z\right)^2\right]t}}\right]\right\} exp\left(\frac{v_z\left[2\left(z+x\sqrt{D_x/D_z}\right)-v_z t\right]}{4D_z\left[1+\left(D_x/D_z\right)^2\right]}\right) \quad (5)$$

The diffusion coefficient used for x-direction is 10 times less than the diffusion coefficient for z-direction. Specifically, the diffusion coefficient used for z-direction is 1.77 x 10^{-4} m/day, while seepage velocity is 0.0025 m/day.

III. RESULTS AND DISCUSSION

The simulated results of the heavy metal transport via diffusion and advection in the soil-groundwater mediaare shown in the surface plots, in Figures 1 to 3, after 1 year, 5 years and 10 years transport.

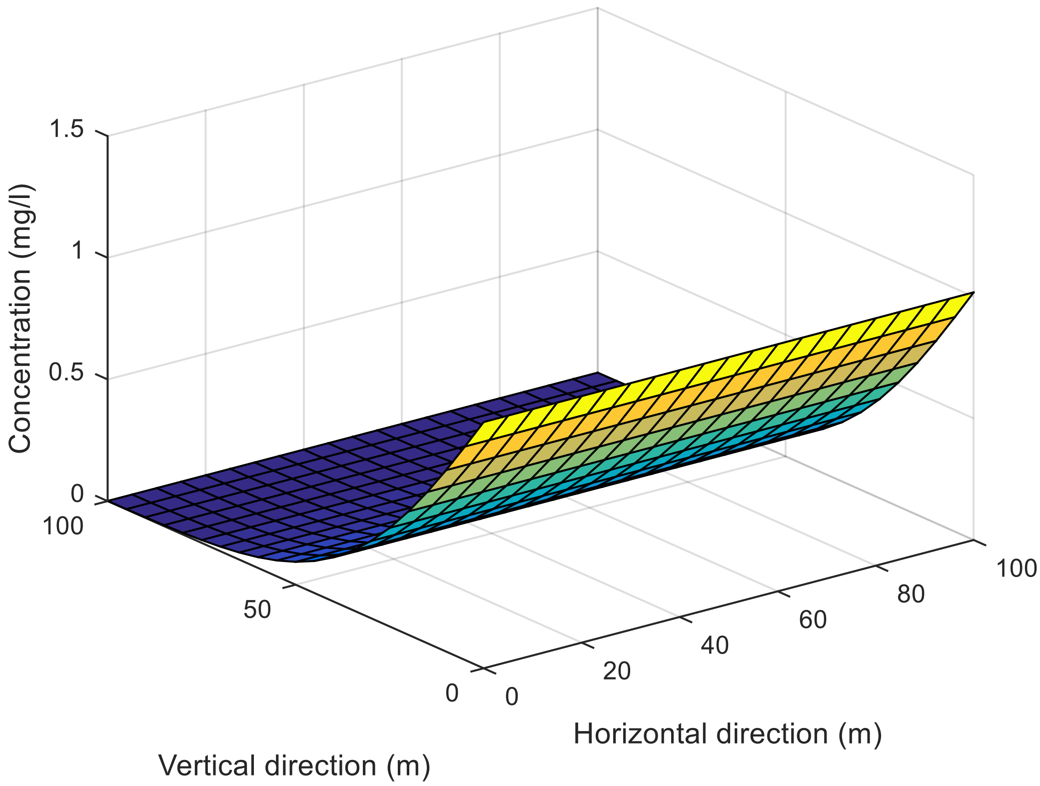

Figure 1: Surface plot of heavy metal transport in soil-groundwater system after 1 year

Figure 1 shows the surface plot of simulated heavy metal transport into soil-groundwater media after one year of its initial release onto the soil. The results indicate that from the initial concentration, the heavy metal had migrated across the entire domain, from the surface to 100 m in both vertical and horizontal directions, with varying concentrationlevels along the grids in both directions.The predicted concentration at the source location near the surface is approximately 1.0120mg/l. The lowest predicted concentration was observed at 100 m depth, which is approximately 0.000782 mg/l. This indicates that the heavy metal contaminant has migrated to this depth but within trace levels.

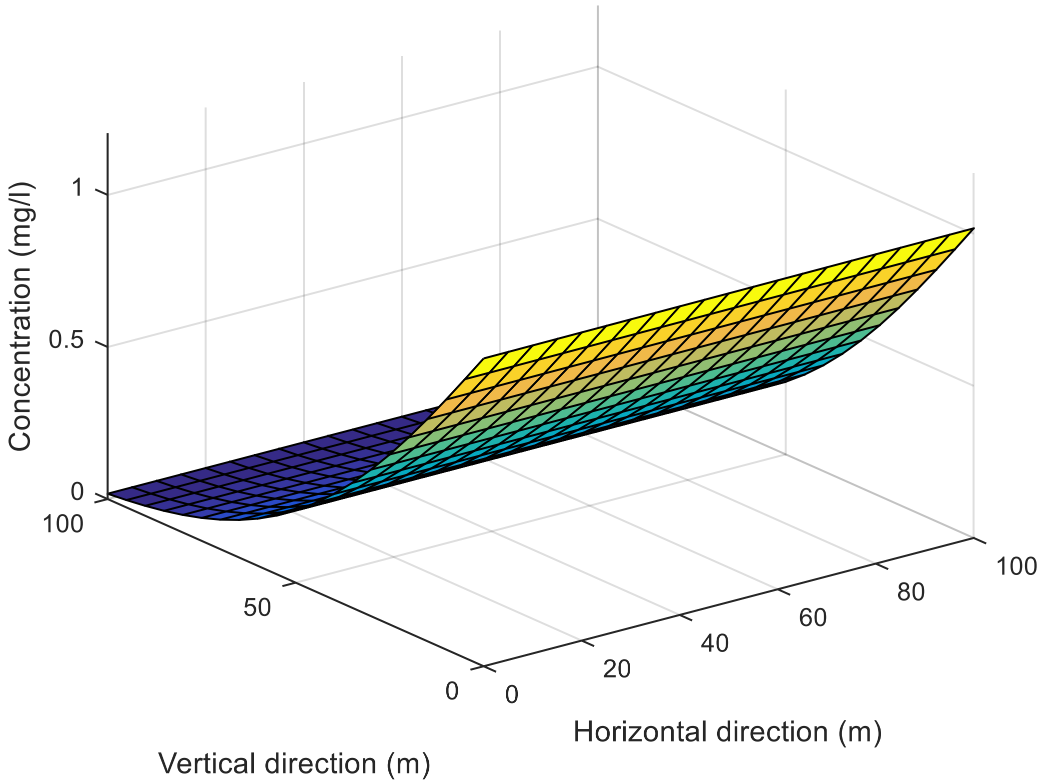

Figure 2: Surface plot of heavy metal transport in soil-groundwater system after 5 years

Figure 2 shows the surface plot of simulated heavy metal transport into soil-groundwater media after five years of its initial release onto the soil. The heavy metal transport in the soil-groundwater media from the surface to 100 m in both vertical and horizontal directions also showed variations in concentration levels, but the magnitudes at corresponding points in vertical and horizontal directionswithin the media are higher compare to the concentration levels recorded after one year. Thus, after five years, the predicted concentration near the surface is approximately 1.01204 mg/l, whilethe lowest predicted concentration at 100 m depth is approximately 0.01763 mg/l. This indicates that the difference in heavy metal concentration recorded near the surface after one year and after five years is negligible, but at 100 m depth, the difference is approximately 0.01685, representing 95.58% increase.

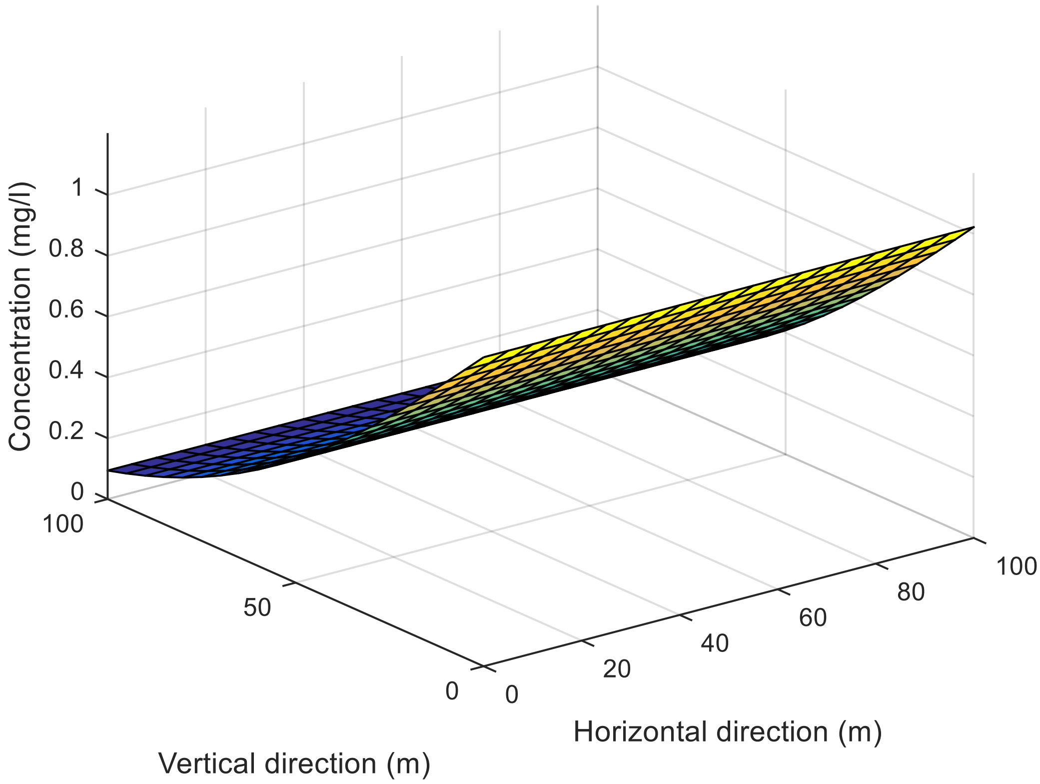

Figure 3: Surface plot of heavy metal transport in soil-groundwater system after 10 years

Figure 3 shows the surface plot of simulated heavy metal transport into soil-groundwater media after ten years at various points in the media across up to 100 m in both vertical and horizontal directions. Like after one year and five years, the concentration of heavy metal in the soil-groundwater media after ten years also varies along the vertical and horizontal directions. However, the concentrations at the corresponding points within the media are higher compare to the concentration levels recorded after one year and five years. The simulated results indicated that after ten years, the concentration near the surface is 1.01598 mg/l. This implies that the concentration did not change significantly from the value recorded after one year (1.0120mg/l) and after five years (1.01204 mg/l) at the same point. Nevertheless, at 100 m depth, the predicted concentration is approximately 0.09383 mg/l. This indicates that the difference in heavy metal concentration recorded near the surface after one year and ten years is relatively negligible (0.00398 mg/l, representing 0.39% increase), but at 100 m depth, the difference is approximately 0.09305 mg/l, representing 99.17% increase. Similarly, the increase in concentration at 100 m depth from five years to ten years is 81.12%.

Overall, thereis visible spreading and downward transport of the metal, with varying concentrations at a given point in the soil-groundwater media. The predicted data, however, indicates a negligible change in concentration level near surface, after one, five and ten years, while at the depths far below the surface recorded significant differences, with concentration levels in the soil-groundwatermedia increasing with increase in years. Interestingly, the concentration of heavy metal at the surface reduced by approximately 80% within the first, five or ten years. This suggests a high rate of mass transfer, likely due to advection, especially during the wet season. In wet (rainy) season, the soil becomes soft and seepage velocity increases, thereby influencing rate of contaminants' transport in soil media. This collaborated the finding by an earlier study that found higher concentration of heavy metal in soil during the wet season compared to the dry season (Ito et al., 2022; Kekwaru et al., 2023).This may also be attributed to influence of geological structures, such as low-permeability clay that strongly binds the heavy metal. Sorption (adsorption and absorption) onto soil particles and hydrodynamic dispersion (Tan et al., 2022) within the unsaturated zone are highly likely to limitthe rapid transport of heavy metals in soil, particularly when the average pore size of soillayers with high clay content is low. Studies have shown that smaller soil particle sizes reduced the movement of contaminants in soil media (Liu et al., 2019).

IV. CONCLUSION

The findings generally show that the heavy metal concentration in the soil-groundwater media exhibit remarkable uniformity across the horizontal plane at any given depth compared to changes in the vertical direction. This suggests a negligible concentration gradient in the horizontal direction, and the lateral spreading is governed purely by radial dispersion.

Furthermore, the simulated concentration at depths up to 60 meters are very low. Thus, for iron, lead, chromium or cadmium contaminants with the similar diffusion coefficient and seepage velocity, the concentration level at range of depth is within or below the standard permissible limits specified for drinking water. Hence, the model provided insights into the transport mechanisms and accumulation of heavy metals in soil and groundwater storage system.

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