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Two-Dimensional Numerical Modelling and Simulation of Pollutant Advection–Dispersion in Choba Creek, Rivers State, Nigeria

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Abstract— *Pollutant transport in river systems poses significant environmental challenges, particularly in water bodies exposed to anthropogenic activities. This study developed and applied a two-dimensional advection–dispersion mathematical model to investigate the temporal and spatial transport behaviour of selected pollutants in Choba Creek, Rivers State, Nigeria. The governing equation was formulated based on the principle of mass conservation and numerically solved using an explicit finite difference method. The longitudinal dispersion coefficient was estimated using an empirical hydraulic relationship, while simulations were conducted for iron (Fe), cadmium (Cd), lead (Pb), phosphate (PO_4^{3-}), nitrate (NO_3^-), and total petroleum hydrocarbons (TPH) over a 300 m computational reach and a six-hour simulation period. The estimated longitudinal dispersion coefficient was 4.18 m^2/s. The simulation results showed rapid increases in downstream pollutant concentrations, approaching approximately constant values of 0.196, 0.006, 0.70, 0.97, 1.82, and 9.85 mg/L for Fe, Cd, Pb, PO_4^{3-}, NO_3^-, and TPH, respectively. The longitudinal concentration–time distributions demonstrated the progressive development of contaminant concentration fields, with elevated concentrations extending downstream as simulation time increased. The broadly similar transport patterns observed among the pollutants suggest that their simulated concentration dynamics were primarily governed by the common hydraulic and dispersion parameters, while differences in concentration magnitude reflected their respective input concentrations. The study demonstrates the potential of advection–dispersion modelling for preliminary assessment of contaminant migration in Choba Creek and provides a foundation for subsequent model validation and improved surface-water quality management.*

Keywords— *Advection–dispersion modelling; Choba Creek; Finite difference method; Longitudinal dispersion coefficient; Pollutant transport; Water quality; Numerical simulation*.

I. INTRODUCTION

Surface-water pollution remains a major environmental challenge, particularly in river systems exposed to increasing anthropogenic activities, urban development, industrial operations and agricultural runoff. Rivers and creeks serve important ecological and socioeconomic functions, including water supply, fisheries, transportation and the maintenance of aquatic ecosystems. However, the introduction of contaminants into these water bodies can alter their physicochemical characteristics, degrade water quality and threaten aquatic organisms and downstream water users. Understanding the mechanisms governing contaminant migration is therefore essential for assessing pollution risks and developing effective water-resource management strategies. Numerical modelling provides a systematic approach for investigating these processes by describing the movement and redistribution of contaminants under specified hydrodynamic and environmental conditions (Mignot et al., 2023; Wang et al., 2023). The transport of dissolved contaminants in flowing water is governed principally by advection, molecular diffusion and hydrodynamic dispersion. Advection describes the movement of contaminants with the mean water velocity, whereas molecular diffusion involves the redistribution of dissolved substances resulting from concentration gradients. Hydrodynamic dispersion represents additional spreading caused by spatial variations in flow velocity, turbulent mixing and other flow-related processes. In natural river systems, these mechanisms interact to determine the movement of contaminant fronts, the development of concentration gradients and the spatial extent of pollutant distributions. Their relative importance depends on factors such as flow velocity, channel geometry, water depth, turbulence intensity and the characteristics of the pollutant source. Consequently, accurate representation of pollutant transport requires mathematical formulations capable of accounting for the relevant physical transport mechanisms (Mignot et al., 2023).

Mathematical models based on the advection–dispersion equation have become established tools for investigating contaminant transport in rivers and other surface-water environments. These models express the conservation of pollutant mass by relating temporal changes in concentration to advective transport, dispersive fluxes and, where applicable, external sources and transformation processes. Depending on the complexity of the flow field and the objectives of the investigation, pollutant transport may be represented using one-, two- or three-dimensional formulations. One-dimensional models are useful where longitudinal transport dominates and transverse concentration gradients are negligible. However, they cannot explicitly describe concentration variations across the channel width. Two-dimensional depth-averaged models provide an intermediate approach by resolving longitudinal and transverse transport while avoiding the computational requirements associated with fully three-dimensional simulations (Mignot et al., 2023). Recent investigations have demonstrated the importance of multidimensional numerical modelling for understanding pollutant transport under complex hydraulic conditions. Wang et al. (2023) investigated pollutant dispersion in an asymmetrical river confluence using a three-

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dimensional hydrodynamic water-quality model. Their findings demonstrated that discharge ratio and channel width-to-depth ratio significantly influenced the lateral extent of pollutant dispersion and the mixing characteristics of the flow. The study highlighted the sensitivity of contaminant distributions to hydraulic conditions and channel configuration, emphasising the importance of representing spatial transport processes when evaluating pollutant migration. Although the investigation focused on a river confluence, its findings provide broader evidence that contaminant transport cannot always be adequately characterised using longitudinal flow conditions alone. The reliability of advection–dispersion simulations depends strongly on the specification of appropriate transport coefficients. In particular, the longitudinal dispersion coefficient is a fundamental parameter describing the spreading of contaminants along the principal flow direction. This coefficient is influenced by the interaction between channel geometry, velocity distribution, turbulent mixing and secondary flow processes. Because direct determination of dispersion coefficients through field tracer experiments may require considerable resources, empirical relationships are frequently employed to estimate these parameters from measurable hydraulic characteristics. Nevertheless, the applicability of such relationships varies among river systems, and the resulting estimates may be sensitive to differences in hydraulic conditions and the characteristics of the datasets used to develop the equations. Despite advances in numerical modelling, uncertainties remain in the formulation and parameterisation of two-dimensional pollutant transport models. In a comprehensive review, Mignot et al. (2023) identified seven formulations of the depth-averaged advection–diffusion equation and eight approaches for determining the associated diffusivity coefficients. The authors reported considerable variation in modelling practices and observed that relatively few investigations included adequate calibration of diffusivity coefficients against experimental or field observations. Their findings indicate that uncertainties in transport parameterisation and limited validation data continue to constrain the reliability and transferability of numerical pollutant transport models. Accordingly, site-specific modelling investigations must clearly identify the assumptions underlying the governing equations, transport coefficients and boundary conditions. These considerations are particularly relevant to river and creek systems in the Niger Delta region of Nigeria, where water bodies may be exposed to multiple potential sources of contamination associated with settlements, industrial activities, transportation and land-use practices. Choba Creek, located in Rivers State, provides a relevant case study for examining the numerical transport of selected water-quality contaminants. The pollutants considered in the present investigation include iron (Fe), cadmium (Cd), lead (Pb), phosphate (PO_4^{3-}), nitrate (NO_3^-) and total petroleum hydrocarbons (TPH). These substances represent different classes of water-quality contaminants, including metals, nutrients and petroleum-related compounds. Their inclusion permits examination of concentration distributions under the adopted transport framework, although the present conservative transport formulation does not explicitly represent their individual chemical transformation or removal mechanisms. A central challenge in modelling pollutant migration in Choba Creek is the need to characterise how contaminant concentrations evolve both along the principal flow direction and across the channel width. A description based solely on downstream concentration measurements may not adequately represent the spatial development of a contaminant field. Similarly, the estimation of a longitudinal dispersion coefficient does not, by itself, establish the temporal response of contaminant concentrations at downstream locations. Numerical simulation offers an approach for integrating the effects of advective flow, dispersion and prescribed pollutant inputs to examine the evolution of contaminant concentration distributions.

The present study adopts a two-dimensional advection–dispersion formulation to investigate pollutant transport in Choba Creek. The governing equation is derived from the conservation of mass and numerically solved using an explicit finite difference method. The longitudinal dispersion coefficient is estimated from the hydraulic characteristics of the creek using an empirical relationship, while the resulting numerical solutions are examined through downstream breakthrough curves, longitudinal and transverse concentration profiles, and two-dimensional spatial concentration maps. These complementary outputs provide a basis for interpreting the temporal development and spatial distribution of pollutant concentrations under the specified simulation conditions. The specific objectives of the study are to formulate and numerically implement a two-dimensional pollutant advection–dispersion model for Choba Creek; estimate the longitudinal dispersion coefficient from the adopted hydraulic parameters; simulate the temporal and spatial concentration distributions of Fe, Cd, Pb, PO_4^{3-}, NO_3^- and TPH; and evaluate the predicted breakthrough characteristics and concentration gradients within the modelled river reach.

II. Materials and Methods

2.1. Description of the Study Areas

The present study considers Choba river located in Rivers State, southern Nigeria, within the wider Niger Delta region. The river was selected for numerical investigation of pollutant advection and dispersion under different hydraulic conditions. The study adopts a consistent two-dimensional transport formulation for the river system, allowing variations in predicted pollutant behaviour to be examined in relation to differences in river-specific hydraulic and geometric parameters.

The Niger Delta is characterised by an extensive network of freshwater channels, streams, rivers and estuarine environments that support domestic activities, agriculture, fisheries and other economic functions. Water quality within these systems may be influenced by municipal wastewater discharge, agricultural runoff, sediment transport and other anthropogenic inputs. Therefore, understanding how contaminants move within individual river channels matters for assessing downstream pollutant exposure and for developing suitable environmental monitoring strategies. The selected river systems are represented using their respective hydraulic characteristics,

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including channel width, mean water depth, average flow velocity and longitudinal dispersion coefficient. These parameters influence the relative contributions of advective transport and hydrodynamic dispersion to contaminant movement. In particular, differences in flow velocity affect the rate of downstream pollutant migration, whereas differences in dispersion coefficients influence the longitudinal spreading of contaminant plumes.

2.2 Development of Mathematical Model for Diffusion and Dispersion

The mathematical model describing pollutant transport in the river system was developed from the principle of conservation of mass applied to a differential control element within the river domain. The objective of the model was to describe the spatial and temporal variation of contaminant concentration in both the longitudinal (x) direction (along the river flow) and the transverse (y) direction (across the river width). The developed governing equation was implemented numerically using MATLAB.

2.2.1 Model Assumptions

The following assumptions were adopted in the development of the model:

i. The system is two-dimensional, with transport occurring only in the longitudinal (x) and transverse (y) directions.
ii. The river is depth-averaged; vertical concentration gradients are neglected.
iii. Flow velocity components in the (x) and (y) directions are uniform within the modeled reach.
iv. Longitudinal and transverse dispersion coefficients are constant.
v. River banks are impermeable; hence, no lateral mass flux occurs across the boundaries.
vi. External pollutant loading is represented through a distributed source term.

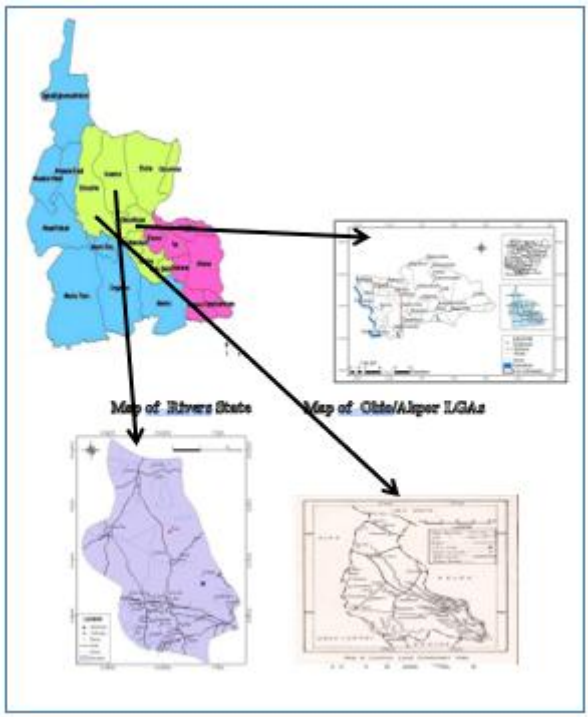


Figure 1: Map of Rivers State, showing the general location of the study area and Map of the relevant Local Government Areas (Obio/Akpor, Emohua, and Ikwerre LGAs)

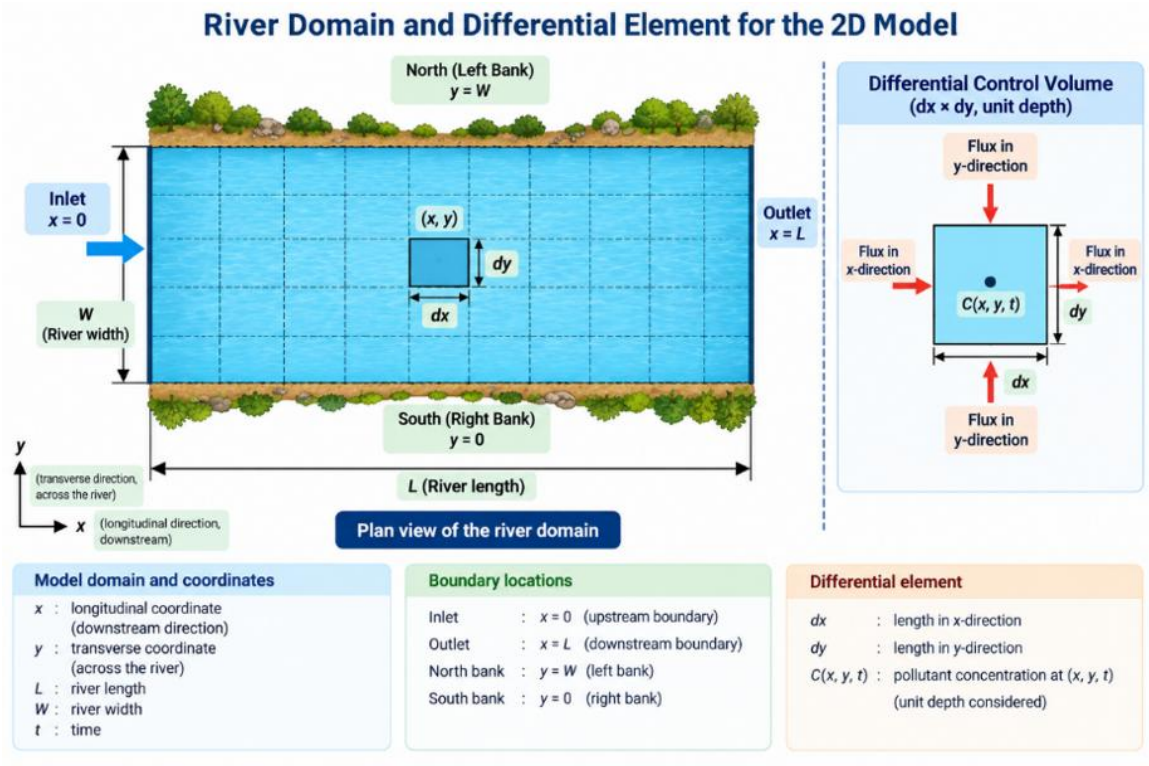


Figure 2: Schematic of the River Domain for the 2D Model

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2.2.2 Governing Equation Derivation

A differential control element of dimensions $dx\,dy$ was considered. Applying the conservation

$\{Rate\ of\ Accumulation\ of\ Pullutant\ in\ River\} = \{Rate\ of\ inflow\ of\ Pullutant\ into\ River\} - \{Rate\ of\ Outflow\ of\ Pollutant\ from\ River\} + \{Source\ of\ Pollutant\ into\ River\}$ (1)

Mathematically equation (1) can be written as;

$$\frac{\partial C_i}{\partial t}dx\,dy = -\left(\frac{\partial J_{x,i}}{\partial x} + \frac{\partial J_{y,i}}{\partial y}\right)dx\,dy + S_i dx\,dy \quad (2)$$

Divide through equation (2) by $dx\,dy$

$$\frac{\partial C_i}{\partial t} = -\left(\frac{\partial J_{x,i}}{\partial x} + \frac{\partial J_{y,i}}{\partial y}\right) + S_i \quad (3)$$

Recall,

Total flux: $$J_{x,i} = uC_i - D_x\frac{\partial C_i}{\partial x} \quad (4)$$

$$J_{y,i} = vC_i - D_y\frac{\partial C_i}{\partial y} \quad (5)$$

Substituting equations (4) & (5) into equation (3)

$$\frac{\partial C_i}{\partial t} = -\frac{\partial}{\partial x}\left(uC_i - D_x\frac{\partial C_i}{\partial x}\right) - \frac{\partial}{\partial y}\left(vC_i - D_y\frac{\partial C_i}{\partial y}\right) + S_i \quad (6)$$

Assuming $u, v, D_x\ and\ D_y$ are assumed to be constants

$$\frac{\partial C_i}{\partial t} = -u\frac{\partial C_i}{\partial x} + D_x\frac{\partial^2 C_i}{\partial x^2} - v\frac{\partial C_i}{\partial x} + D_y\frac{\partial^2 C_i}{\partial y^2} + S_i \quad (7)$$

Rearranging equation (7)

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} + v\frac{\partial C_i}{\partial x} = D_x\frac{\partial^2 C_i}{\partial x^2} + D_y\frac{\partial^2 C_i}{\partial y^2} + S_i \quad (8)$$

Where: D_x = longitudinal dispersion coefficient, D_y = transverse dispersion coefficient. C − Pollutant concentration, u − River velocity in x − direction, v − River velocity in y-direction, D_x − Longitudinal dispersion coefficient, D_y − Transverse dispersion coefficient

S_c − External pollutant source term, L – River length, W – River width, x - Longitudinal coordinate, y - Transverse coordinate, t – time

Initial condition

$$0 \le x \le L,\ 0 \le y \le W \quad (9)$$

The initial pollutant distribution is $C(x, y, 0) = C_0(x, y)$ (10)

Boundary condition at $x = 0$

1) $$C(0, y, t) = C_{in}(t) \quad (11)$$

Downstream boundary at $x = L$

$$\frac{\partial C}{\partial x}(L, y, t) = 0 \quad (12)$$

River-bank conditions

$$y = 0 \text{ and } y = W \quad (13)$$

Therefore,

$$\frac{\partial C}{\partial y}(x, 0, t) = 0 \text{ and } \frac{\partial C}{\partial y}(x, W, t) = 0 \quad (14)$$

2.2.3 Estimation of Dispersion Coefficient

The longitudinal dispersion coefficient was estimated using the Fischer relation provided as Equation (3.14) , we have

$$D_x = 0.011\frac{U^2W^2}{d\sqrt{gdS}} \quad (15)$$

where:

U = mean stream velocity, (m/s); W = river width (m); d = mean depth (m); g = gravitational acceleration, (m/s^2); S = channel slope.

The shear velocity is;

$$u_* = \sqrt{gdS} \quad (16)$$

III. Results and Discussion

This section presents and discusses the numerical simulation results of pollutant advection–dispersion in Choba Creek, Rivers State, Nigeria. The analysis focuses on the temporal and spatial transport behaviour of six selected pollutants: iron (Fe), cadmium (Cd), lead (Pb), phosphate (PO_4^{3-}), nitrate (NO_3^-), and total petroleum hydrocarbons (TPH). The simulation results are presented using downstream breakthrough curves and longitudinal concentration–time distributions over a six-hour simulation period and a 300 m computational reach. The breakthrough curves illustrate the temporal evolution of pollutant concentrations at the downstream monitoring location, while the longitudinal concentration profiles describe the movement and spreading of contaminant fronts along the creek. The results are interpreted in relation to the combined influence of advective transport and hydrodynamic dispersion, with particular emphasis on concentration development, spatial redistribution, and the implications of the predicted transport behaviour for water quality in Choba Creek.

3.1. Iron (Fe) transport

Figure 3 illustrates the temporal variation of iron concentration at the downstream monitoring point. The concentration increases rapidly from approximately zero to 0.196 mg/L within the early simulation period before remaining nearly constant throughout the six-hour period.

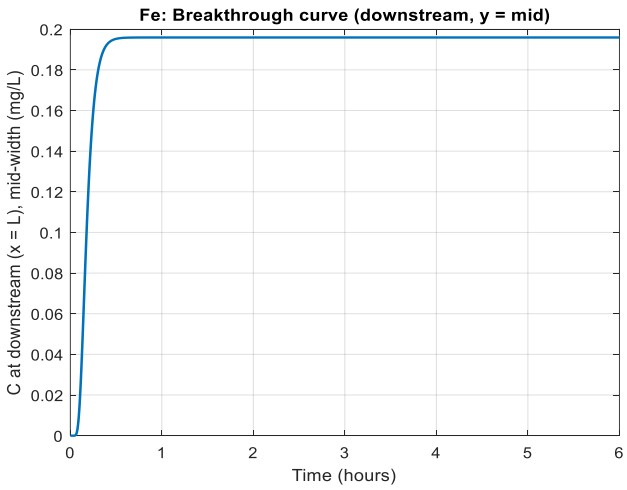


Figure 3: Breakthrough Curve of Fe at Downstream Location ($x = L$, y = mid-width)

This behaviour indicates rapid development of downstream iron concentration followed by an approach towards quasi-steady conditions under the prescribed pollutant input. The sharp concentration increase and subsequent plateau reflect the simulated advective–dispersive transport response.

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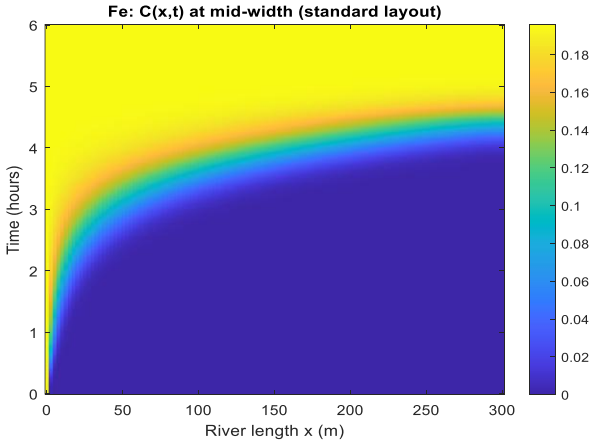


Figure 4: Longitudinal Concentration Distribution $C(x,t)$of Fe at Mid-Width

Figure 4 presents the spatial and temporal evolution of iron concentration along the 300 m modelled reach. The colour progression from dark blue to yellow represents increasing iron concentration, while the curved transition zone indicates the movement and spreading of the contaminant front. Higher concentrations develop progressively farther downstream as simulation time increases, demonstrating the combined influence of longitudinal advection and dispersion. The plot indicates that approximately five hours are required for elevated concentrations to extend across most of the simulated reach.

3.2. Cadmium (Cd) transport

Figure 5 shows a rapid increase in downstream cadmium concentration, reaching approximately 0.006 mg/L during the initial simulation period. Thereafter, the concentration remains nearly constant until six hours.

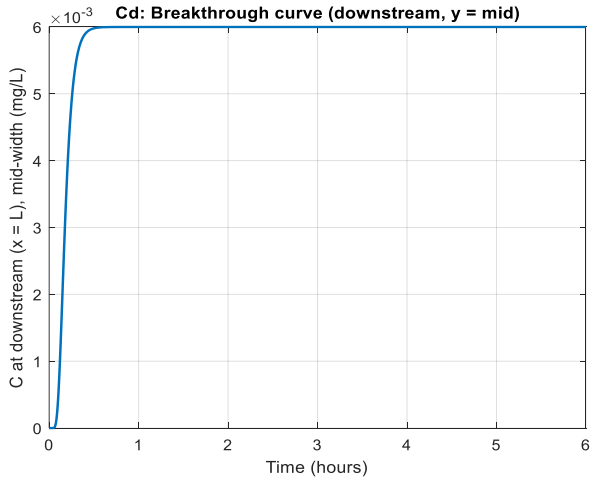


Figure 5: Breakthrough Curve of Cd at Downstream Location (x = L, y = mid-width)

This response suggests that the downstream concentration approaches the prescribed input concentration relatively quickly, with the system subsequently attaining a quasi-steady condition. The curve demonstrates the temporal response of cadmium transport under the adopted hydraulic and boundary conditions.

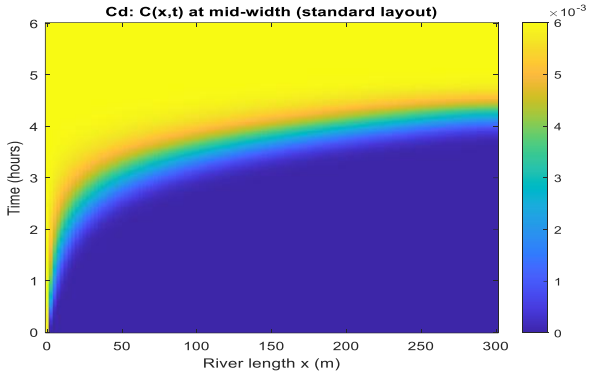


Figure 6: Longitudinal Concentration Distribution of Cd, C(x,t) at Mid-Width

Figure 6 illustrates the longitudinal distribution of cadmium concentration over the six-hour simulation period. Initially, elevated concentrations are restricted to the upstream region, while the downstream section exhibits relatively low concentrations. As time progresses, the concentration front advances downstream, and the transition between contaminated and less-contaminated regions becomes more extensive. The progressive colour change from blue to yellow indicates increasing concentration and the development of a broader concentration field.

3.3. Lead (Pb) transport

Figure 7 presents the downstream breakthrough behaviour of lead. The simulated concentration increases sharply from zero to approximately 0.70 mg/L before stabilising during the early simulation period.

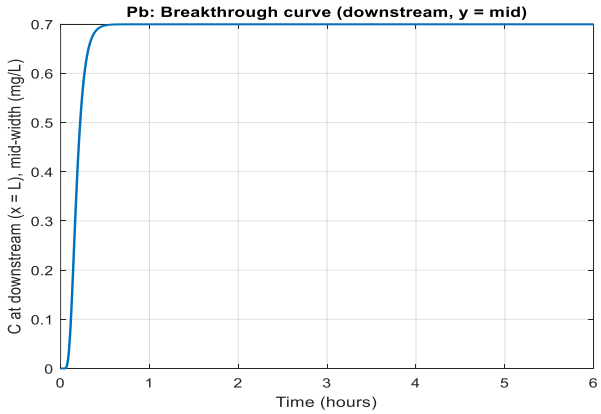


Figure 7: Breakthrough Curve of Pb at Downstream Location (x = L, y = mid-width)

The rapid increase indicates the development of lead concentration at the downstream monitoring point, while the subsequent plateau suggests an approach towards quasi-steady conditions. The result demonstrates the predicted transport response of lead within the modelled creek reach.

Figure 8 shows the evolution of lead concentration along the creek. At the beginning of the simulation, elevated concentrations are concentrated near the upstream boundary, while downstream concentrations remain low. With increasing simulation time, the contaminant front extends along the channel, accompanied by a gradual reduction in longitudinal

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concentration gradients. By approximately five hours, elevated concentrations occupy most of the computational domain, indicating substantial development of the simulated concentration field.

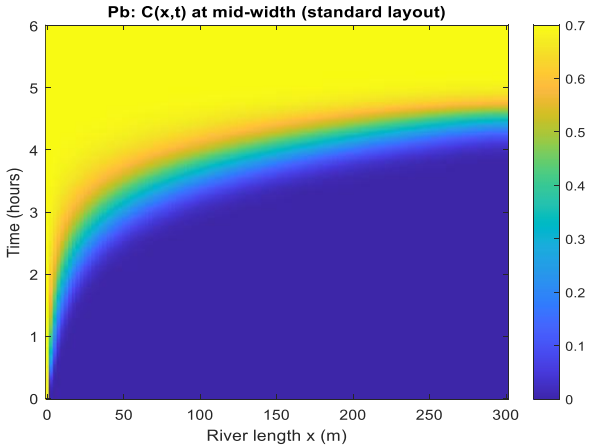


Figure 8: Longitudinal Concentration Distribution C(x,t) of Pb at Mid-Width

3.4. Phosphate (PO_4^{3-}) transport

Figure 9 illustrates the temporal variation of phosphate concentration at the downstream monitoring location. The concentration increases rapidly from zero to approximately 0.97 mg/L before approaching a nearly constant value.

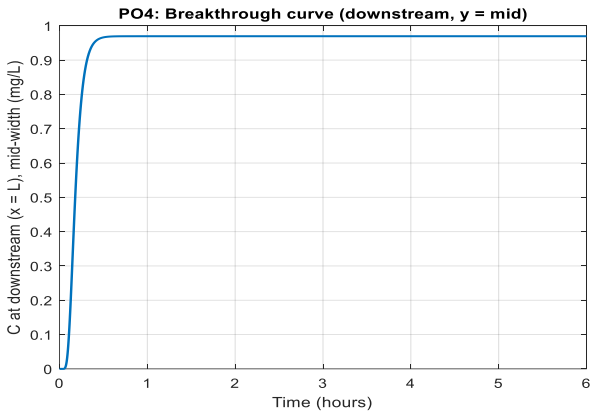


Figure 9: Breakthrough Curve of PO_4^{3-} at Downstream Location (x = L, y = mid-width)

This behaviour indicates rapid development of downstream phosphate concentration under the specified simulation conditions. The stable concentration observed during the remaining simulation period suggests that the modelled system approaches quasi-steady transport conditions.

Figure 10 presents the longitudinal and temporal distribution of phosphate concentration. The initially elevated concentrations near the upstream boundary progressively extend towards downstream locations. The transition from low-concentration blue regions to high-concentration yellow regions illustrates the development of the phosphate concentration field. The curved concentration front becomes more extensive with time, indicating longitudinal spreading as the simulation progresses.

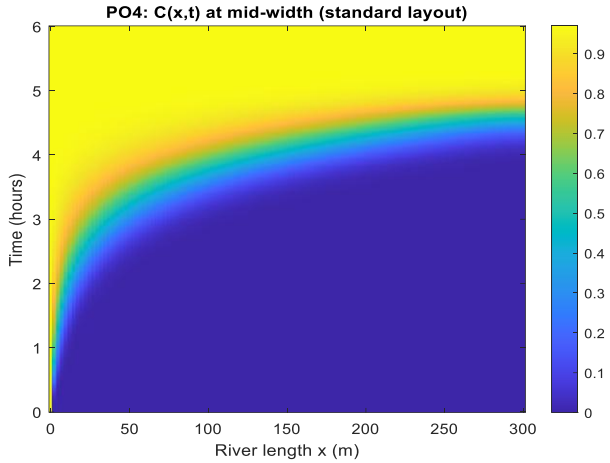


Figure 10: Longitudinal Concentration Distribution C(x,t) of PO_4^{3-} at Mid-Width

3.5. Nitrate (NO_3^-) transport

Figure 11 shows the simulated downstream nitrate concentration increasing rapidly from approximately zero to 1.82 mg/L during the initial simulation period.

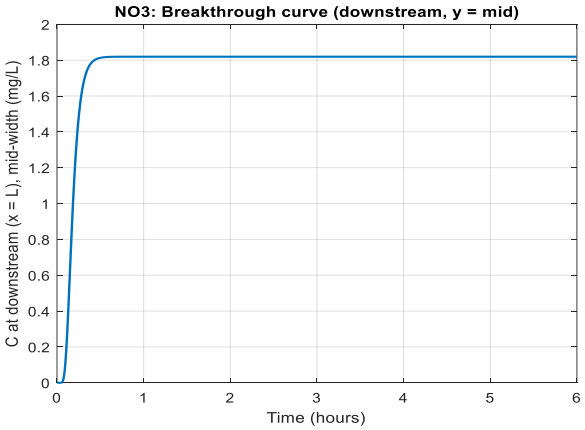


Figure 11: Breakthrough Curve of NO_3^- at Downstream Location (x = L, y = mid-width)

The concentration subsequently remains nearly constant throughout the six-hour simulation. This response indicates the rapid establishment of downstream nitrate concentration under the prescribed transport conditions, followed by an approach towards quasi-steady behaviour.

Figure 12 illustrates the temporal development of nitrate concentration along the modelled creek reach. Initially, the highest concentrations occur near the upstream boundary, while lower concentrations prevail farther downstream. As simulation time increases, the concentration front progressively extends along the river length. The transition from dark blue to yellow indicates increasing nitrate concentration, while the curved concentration boundary illustrates the combined effects of contaminant movement and longitudinal spreading.

3.6. Total Petroleum Hydrocarbons (TPH) transport

Figure 13 presents the temporal variation of total petroleum hydrocarbon concentration at the downstream monitoring

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location. The concentration increases sharply from zero to approximately 9.85 mg/L before approaching a stable value during the early simulation period.

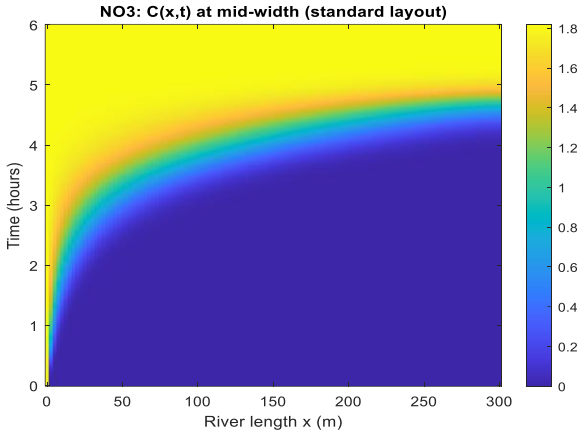


Figure 12: Longitudinal Concentration Distribution C(x,t) of NO_3^- at Mid-Width

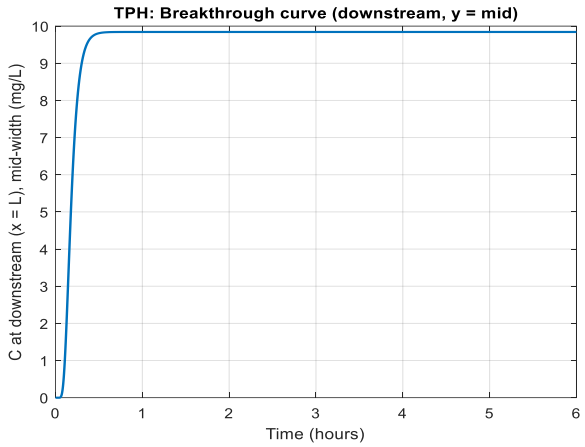


Figure 13: Breakthrough Curve of TPH at Downstream Location (x = L, y = mid-width)

This behaviour indicates rapid development of downstream TPH concentration under the adopted transport conditions. However, the model does not explicitly represent petroleum hydrocarbon degradation, volatilisation or adsorption; therefore, the result describes conservative transport rather than the complete environmental fate of petroleum hydrocarbons.

Figure 14 shows the spatial and temporal evolution of TPH concentration along the 300 m computational reach. During the early simulation period, elevated concentrations occur predominantly near the upstream boundary. As time progresses, the concentration front advances downstream, with the transition from blue to yellow indicating increasing concentrations. By approximately five hours, elevated TPH concentrations extend across most of the modelled reach, demonstrating the progressive development of the concentration field through advective–dispersive transport.

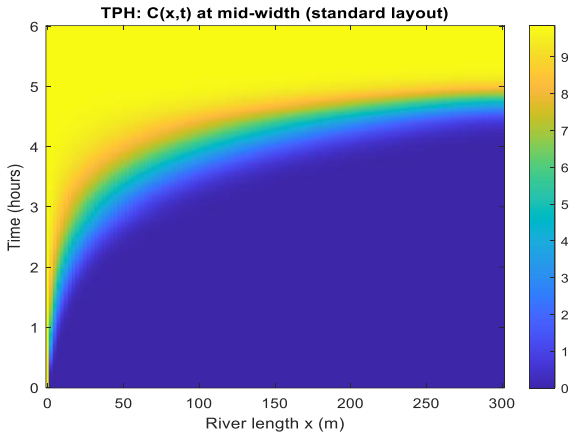


Figure 14: Longitudinal Concentration Distribution C(x,t) of TPH at Mid-Width

IV. CONCLUSION

This study investigated the temporal and spatial transport of selected pollutants in Choba Creek, Rivers State, Nigeria, using a two-dimensional advection–dispersion mathematical model solved numerically through the finite difference method. The investigation considered six pollutants, namely iron (Fe), cadmium (Cd), lead (Pb), phosphate (PO_4^{3-}), nitrate (NO_3^-), and total petroleum hydrocarbons (TPH), over a 300 m computational reach and a six-hour simulation period. The results were evaluated using downstream breakthrough curves and longitudinal concentration–time distributions to examine contaminant migration under the prescribed hydraulic and boundary conditions. The simulated breakthrough curves showed rapid increases in downstream pollutant concentrations, followed by approximately constant values of 0.196, 0.006, 0.70, 0.97, 1.82, and 9.85 mg/L for Fe, Cd, Pb, PO_4^{3-}, NO_3^-, and TPH, respectively. The longitudinal concentration distributions illustrated the progressive development of contaminant concentration fields along the creek, with elevated concentrations extending towards downstream locations as simulation time increased. These results demonstrate the ability of the adopted mathematical framework to represent temporal concentration changes and longitudinal pollutant spreading under specified simulation conditions. The broadly similar concentration patterns observed among the pollutants suggest that their simulated transport behaviour was primarily controlled by the common hydraulic and dispersion parameters, while differences in concentration magnitude reflected the respective pollutant input concentrations. Overall, the study demonstrates the potential application of advection–dispersion modelling for investigating pollutant transport in Choba Creek. The developed framework provides a basis for preliminary assessment of contaminant migration and downstream concentration development. Nevertheless, the findings represent numerical predictions under simplified transport conditions and require field-based validation before they can be used for reliable environmental risk assessment or water-quality management decisions.

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