



Application of Darcy Tools and Advection–Dispersion Models to Predict the Spatial and Temporal Variations of Contaminants in Borehole Water: A Case Study of Attisa Kingdom, Yenagoa

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Abstract: This study integrated groundwater quality assessment with Darcy-based mass-flux analysis and the Advection–Dispersion Model (ADM) to investigate contaminant transport in the shallow, unconfined aquifer of Akaba-Attisa in the Niger Delta, Nigeria. Groundwater samples were collected from three boreholes (A–C) aligned along the inferred flow direction and analyzed for physicochemical parameters, major ions, nutrients, and trace metals using standard WHO and NSDWQ protocols. Numerical modelling was applied to quantify groundwater flow, contaminant fluxes, and dominant transport mechanisms. Results indicate a Ca–Mg–HCO₃ groundwater facies with increasing mineralisation and nitrate contamination toward the mid-gradient well (B), identified as the plume core. Computed groundwater velocity (0.37 m/day) reflects a slow but persistent flow regime typical of shallow aquifers. Darcy-based mass flux calculations show that conservative solutes such as nitrate, TDS, chloride, bicarbonate, and hardness exhibit the highest fluxes, with a consistent hierarchy of $B > C > A$. ADM results further confirm that advective fluxes exceed dispersive fluxes by more than an order of magnitude for most parameters, supported by Peclet numbers greater than unity, indicating advection-dominated transport. Sensitivity analysis demonstrates that reasonable uncertainty in hydraulic conductivity, porosity, and dispersion coefficients does not alter the dominance of advection or the observed plume structure. Public health evaluation reveals nitrate exceedances at downgradient wells, implying sustained advective delivery and elevated chronic exposure risk. The combined Darcy–ADM framework provides a robust basis for linking groundwater flow dynamics with contaminant migration and health risk, offering a valuable tool for groundwater protection and management in shallow aquifer systems.

Keywords: ADM, NSDWQ, Ca–Mg–HCO₃, TDS, $B > C > A$

Nomenclature:

Vocs: Volatile Organic Compounds
ADM: Advection–Dispersion Model
AAS: Atomic Absorption Spectroscopy
TDS: Total Dissolved Solids

I. INTRODUCTION

Groundwater constitutes a primary source of potable

water for domestic, agricultural, and industrial uses in many developing regions, including Nigeria. An ideal borehole water supply is presumed to meet required water quality standards for multiple uses, being safe, potable, affordable, reliable, and sustainable, with adequate yield and favourable aquifer characteristics [1]. Such water should be free of harmful contaminants, transparent, odourless, tasteless, within acceptable limits of turbidity, pH, and hardness, and easily accessible, economically viable, and environmentally sustainable. These requirements informed the provision of boreholes in communities within the Atissa Kingdom, Yenagoa, Bayelsa State.

Yenagoa, the capital of Bayelsa State, evolved from ancient settlements within the Atissa Kingdom, whose name is derived from the Epie words Yen (home) and Oguo (founder) [2]. Over time, modern Yenagoa has incorporated several sibling towns from the Epie and Atissa Kingdoms. These communities depend heavily on borehole water as their primary source of drinking and domestic water supply, making groundwater quality and sustainability critical to public health and socio-economic development.

Despite the presumed safety of groundwater, borehole water is increasingly vulnerable to contamination from diverse sources. Groundwater contaminants may be physical, chemical, biological, radiological, or organic in nature, each posing varying degrees of health risk. Physical pollutants such as sediment, turbidity, and color can degrade water quality and interfere with treatment processes [3]. Chemical contaminants-including heavy metals (lead, mercury, arsenic), nitrates, fluoride, chlorides, sulfates, and hardness-are associated with chronic health effects [4]. Biological contaminants such as bacteria (e.g., E. coli, Salmonella), viruses, and protozoa can cause waterborne diseases [5] while radiological contaminants (uranium, radium, radon) increase long-term cancer risks. Organic contaminants, including pesticides, herbicides, volatile organic compounds (VOCs), and disinfection by-products, further compound groundwater quality concerns [6].

These contaminants enter borehole water through both geogenic and anthropogenic pathways, including agricultural runoff, industrial activities, improper waste disposal, surface water infiltration, and inadequate well construction or maintenance practices [7]. In Nigeria, several studies have reported groundwater contamination exceeding regulatory limits, particularly for nitrates and dissolved ions [8]. Exposure to such contaminants has been linked to cancer, neurological damage,

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reproductive disorders, and ecosystem degradation [9].

Understanding contaminant movement within aquifer systems requires linking groundwater flow processes with solute transport mechanisms. Darcy's Law governs groundwater flow and advective mass transport, while the Advection–Dispersion Model (ADM) explains plume spreading through mechanical dispersion and molecular diffusion [10]. Predictive modelling based on these principles plays a crucial role in simulating contaminant transport processes, such as advection, dispersion, adsorption, and decay, thereby supporting effective groundwater management, protection, and remediation strategies [11].

The Darcy Tools model is a numerical modelling framework designed explicitly for simulating groundwater flow and contaminant transport. Built upon Darcy's Law and mass transport equations, it has been widely applied in contaminant fate and transport analysis, groundwater resource management, and remediation design [12]. However, in the Atissa Kingdom, the spatial and temporal variations of contaminants in borehole water remain poorly understood, and existing studies primarily rely on static concentration comparisons rather than physically based transport modelling.

This limitation creates a critical research gap, as the absence of integrated flow–transport modelling limits the ability to accurately predict contaminant migration, persistence, and exposure risks within the aquifer system. Therefore, this study applies Darcy Tools and the Advection–Dispersion Model to simulate groundwater flow and contaminant transport in the Atissa Kingdom aquifer. The objective is to predict the spatial and temporal variations in contaminants in borehole water and to identify effective groundwater management strategies that mitigate health and environmental risks associated with contaminant exposure.

II. MATERIALS AND METHODOLOGY

A. Study Area and Data Description

Hand-dug wells and boreholes are used to access the shallow aquifer system underlying the research region, Akaba-Attisa. Three boreholes (A, B, and C) were sampled at a borehole spacing of 100 m, a total flow path of 200 m, a well depth at water level of 1.83 m, and a hydraulic head range of 27.2–24.6 m, all of which were aligned with the inferred groundwater flow direction. According to Ijaola and Sakwe [13], Fig. 1 depicts the map of the Akaba-Attisa kingdom between latitudes 4°55'29' N and longitudes 6°15'51' E.

The collected water samples were analysed at the Niger Delta University Central Research Equipment Laboratory on Wilberforce Island, Bayelsa State, for physicochemical and chemical water quality parameters. Physicochemical parameters analyzed include pH, salinity, conductivity, turbidity, TDS, TSS, nitrate, chloride, sulphate, bicarbonate, alkalinity, hardness, major cations, and trace metals. The chemical water quality parameters were analysed using Atomic Absorption Spectroscopy (AAS) and concentrated HNO₃ per the WHO and EC standards. After this, the mean values at each location (A, B, C) were interpreted, discussed, and analysed using numerical modelling, such as Darcy Tools and the Advection–Dispersion Model.



[Fig.1: Map of the Atissa Kingdom Showing Sampling Boreholes in Red Dots]

B. Numerical Modelling

The numerical modelling used in this study is limited to Darcy Tools and the Advection–Dispersion Model. Based on Darcy's Law, Darcy Tools is a numerical modelling program used to predict mass transport and fluid flow in porous media. It is frequently used to simulate the flow of pollutants, heat, gas, or groundwater through rock and soil in Hydrogeology, Environmental Engineering, and Geotechnical investigations. The essential features include 3D modelling, multiphase flow modelling, Reactive transport, and Flexible boundary conditions, which are combined with tools such as MATLAB, COMSOL, and ParaView for visualisation. Two essential modules in Darcy Tools are the model components, including the grid generator and flow solver. Transport solver post-processors are widely used in domains such as groundwater hydrology, contaminant transport, nuclear waste disposal, and civil and geotechnical engineering.

Darcy's Law states that:

$$Q = -K \times A \times \frac{dh}{dl} \dots (1)$$

Where

Q = specific discharge (m/s)

K = hydraulic conductivity (m/s)

$\frac{dh}{dl}$ = hydraulic gradient (i)

And since Darcy's law describes groundwater flow through a porous medium for a specific discharge, and can be shown as

$$q = ki \dots (2)$$

Where

▪ q = Darcy flux (m/s)

▪ K = hydraulic conductivity (m/s)

▪ i = hydraulic gradient (–)

To know the rate at which contaminant flows, we will consider the Seepage (linear) groundwater velocity, which is denoted as

$$v = \frac{q}{n} = \frac{ki}{n} \dots (3)$$

Where

▪ q = Darcy flux (m/s)

▪ K = hydraulic conductivity (m/s)

▪ i = hydraulic gradient (–)

▪ n = Effective porosity

To estimate how far contaminants could move between boreholes, mass flux,

which is the product of flow discharged and contamination rate, can be expressed mathematically as

$$\text{Mass flux} = Q \times C \dots (4a)$$

Or

Advective contaminant mass flux

$$J = vC \dots (4b)$$

Where

- J = mass flux (mg m⁻² day⁻¹)
- C = solute concentration (mg/L)
- Q = groundwater discharge
- V = Seepage (linear) groundwater velocity

Since Darcy's law describes groundwater flow through a porous medium, given the following Field Data as measured in this Study in a shallow unconfined aquifer like Yenegoa

- Borehole spacing: 100 m (A-B, B-C)
- Hydraulic head range: 27.2 – 24.6 m
- Total flow length (A-C): 200 m
- Aquifer depth (screened): 1.83 m

Thus, assuming typical shallow sandy aquifer properties (clearly stated):

$$K = 1.0 \times 10^4 \text{ m/s}$$

Effective porosity $n = 0.30$

Hence:

C. Hydraulic Gradient

$$i = \frac{\Delta h}{L} = \frac{27.2 - 24.6}{200} = 0.013$$

Similarly, Darcy Flux and Groundwater Velocity can also be calculated, thus.

Darcy (specific) discharge

$$q = ki = (1.0 \times 10^4)(0.013) = 1.3 \times 10^6 \text{ m/s}$$

Seepage velocity

$$v = \frac{q}{n} = \frac{ki}{n} = \frac{1.3 \times 10^{-6}}{0.30} = 4.33 \times 10^{-6} \text{ m/s}$$

Converting to
m/day

$$v = \frac{4.33 \times 10^{-6} \text{ m}}{s} \times 86400 = 0.374112 \text{ m/day}$$

i. Darcy-Based Contaminant Flux Calculations

Using Location B (maximum concentrations) in Table 2 below to represent the moving plume core.

For instance, nitrate at location B

$$J = 0.37 \times 70 = 25.9 \text{ mgm}^2 \text{ day}^{-1}$$

Which is the Mass flux that represents contaminants' movement between the observed wells located at A, B, and C as indicated in Table 3? Thus, this was done for all contaminant concentrations observed in the wells listed in Table 2, as indicated in Table 3, because Flux is calculated separately for each borehole (A, B, and C) to show spatial variation.

On the other hand, the Advection-Dispersion Model describes how pollutants, solutes, or heat move through porous media such as soil or rock due to fluid flow (advection) and spreading (dispersion and diffusion). It is one of the most widely used models in hydrogeology, environmental science/ engineering, and chemical engineering.

The hydraulic gradient, concentration gradient, advective mass flux, dispersion coefficient (using field data), dispersive flux, ADM diagnostic (which is the process of domination), and pecllet number (which is the standard for ADM) will all

be computed using the same field data as measured and the same assumed parameters given above to also validate the ADM model in accordance with Darcy law.

After calculating the hydraulic gradient and groundwater discharge over a 200m length and qualifying the water quality, the data were combined to estimate how far contaminants could travel between boreholes. Using mass flux, which is the product of flow discharged and contamination rate/values on Table 2 below, using Location B (maximum concentrations) to represent the moving plume core, hence it can be expressed as gradient A-B. For instance, nitrate at location A-B-C, which is as follows:

Table I: Extract of Nitrate Value from Table 2

Locations	Values of NO ₃ ⁻¹
A	37
B	70
C	59

Thus, the gradient equals

$$\frac{dc}{dx} = \frac{70 - 37}{100} = 0.33 \text{ mg/l}$$

Where:

$$\frac{dc}{dx} = \text{change in concentrations over change in distance}$$

Then the Advective mass flux

$$J_{adv} = VC \dots (5)$$

$$J_{adv} = 0.37 \times 70 = 25.9 \text{ mgm}^2 \text{ day}^{-1}$$

Where

- J = mass flux (ADM) (mg m⁻² day⁻¹)
- C = solute concentration (mg/L)

While the Hydrodynamic dispersions

$$D = \alpha_L V \dots (6)$$

According to the dimension from 100 to 200, the scale of the aquifer $\alpha_L = 10$

$$D = 10 \times 0.37 = 3.7 \text{ m}^2/\text{day}$$

So that the Dispersive flux will then be

$$J_{disp} = -D \frac{dc}{dx} \dots (7)$$

$$J_{disp} = -3.7 \times 0.33 = -1.22 \text{ mg/l}$$

For the model (ADM diagnostic)

$$\frac{J_{adv}}{J_{disp}} \dots (8)$$

$$\frac{J_{adv}}{J_{disp}} = \frac{25.9}{1.22} = 21.229$$

Finally, to check the ADM Standard using the Peclet number, which is

$$Pe = \frac{vL}{D} \dots (9)$$

$$Pe = \frac{vL}{D} = \frac{0.37 \times 100}{3.7} = 10$$

Meaning if $Pe > 1$, Advection is a controlled plume Or $Pe > 1 \rightarrow$ advection-dominated transport, Confirms plume migration $A \rightarrow B \rightarrow C$

Thus, this was done for all contaminant concentrations observed in the wells listed in Table 2 below, as indicated in Table 4 below, because ADM was calculated separately for each borehole (A, B, and C) to show spatial variation.



D. Sensitivity Analysis

Sensitivity analysis is a methodical assessment of how changes to input parameters affect model outputs and interpretations. When measurements or assumptions in groundwater research change marginally, it helps to validate the results. While specific parameters were kept constant, others were changed by 25% to account for field uncertainty in shallow aquifers. Next, the impact on mass flow ($J = vC$), seepage velocity (v), and plume interpretation was assessed.

III. RESULTS AND DISCUSSION

A. Interpretations of Observed Contaminant at Well Locations

Table 2 below shows the water-quality dataset for sampling points A, B, and C at the Akaba-Attisa community. Location B shows the highest ionic strength, with elevated NO_3^- and Cl^- , indicating the most significant anthropogenic influence. Location C appears to be more acidic, tending towards moderate mineralisation, with Potential risk for metal mobilisation. The lowest mineral content was observed at location A, indicating that the parameters are closer to background groundwater conditions.

Generally, the groundwater system is predominantly a Ca–Mg– HCO_3^- type, with increasing mineralisation and nitrate contamination toward Point B. Variations in pH and ionic strength suggest differences in aquifer geochemistry, residence time, and anthropogenic impact.

Table II: Physicochemical Parameters for Sampled Boreholes at Akaba-Attisa

Parameter	A	B	C
Ph	6.2	7.8	5.7
Salinity (Sal)	0.21	0.25	0.23
Conductivity ($\mu\text{S}/\text{cm}$)	236	490	384
Turbidity (NTU)	0.45	0.7	0.55
TDS (mg/L)	118	245	192
TSS (mg/L)	0.4	0.55	0.45
NO_3^- (mg/L)	37	70	59
Cl^- (mg/L)	48	65	58
SO_4^{2-} (mg/L)	22	31	27
HCO_3^- (mg/L)	64	88	72
Total Alkalinity (TA)	90	120	110
Total Hardness (TH)	230	320	285
Ca^{2+} (mg/L)	48	72	66
Mg^{2+} (mg/L)	32	50	45
Na^+ (mg/L)	40	66	58
K^+ (mg/L)	8	12	10
Fe (mg/L)	0.03	0.04	0.035
Mn (mg/L)	0.01	0.02	0.015

N/B that A rep location A, B rep location B, and C rep Location C.

B. Groundwater Flow Characteristics and Mass Flux Calculations

The computed groundwater velocity (0.37 m/day) indicates a slow but persistent flow regime typical of shallow unconfined aquifers. Flow direction was from Location A (upgradient) through B to C (downgradient).

Mass flux calculations revealed that conservative solutes (TDS, nitrate, chloride, hardness, bicarbonate) exhibited the

highest fluxes, with a consistent spatial pattern, confirming Location B as the plume core and primary transport zone.

C. Darcy-Based Contaminant Flux Calculations A-B-C

Table III: Calculated Values of Contaminants Movement Between the Observed Wells Located at A, B, and C

Parameter	Unit	A (Flux)	B (Flux)	C (Flux)
Ph	–	–	–	–
Salinity	mg/L	0.078	0.093	0.085
Conductivity*	$\mu\text{S}/\text{cm}$	–	–	–
Turbidity	NTU	0.17	0.26	0.2
TDS	mg/L	43.7	90.7	71
TSS	mg/L	0.15	0.2	0.17
NO_3^-	mg/L	13.7	25.9	21.8
Cl^-	mg/L	17.8	24.1	21.5
SO_4^{2-}	mg/L	8.1	11.5	10
HCO_3^-	mg/L	23.7	32.6	26.6
Total Alkalinity	mg/L	33.3	44.4	40.7
Total Hardness	mg/L	85.1	118.4	105.5
Ca^{2+}	mg/L	17.8	26.6	24.4
Mg^{2+}	mg/L	11.8	18.5	16.7
Na^+	mg/L	14.8	24.4	21.5
K^+	mg/L	3	4.4	3.7
Fe	mg/L	0.011	0.015	0.013
Mn	mg/L	0.004	0.007	0.006

Conductivity and pH are indicators, not transported mass.

From Table 3, it was observed that for most conservative parameters: $J_B > J_C > J_A$, confirming that there is a maximum contaminant mass transport at Location B, Down-gradient attenuation toward Location C, and Background conditions at Location A. Total Hardness, TDS, HCO_3^- , NO_3^- , Cl^- , and Na^+ are the dominant flux contributors with the highest mass fluxes. These parameters are conservative, move primarily by groundwater advection, and are defined as the core contaminant plume.

The basic hydro-chemical foundation for interpreting pollutant transport pathways is provided by the measured groundwater quality values shown in Table 2. The spatial differences in pH, dissolved solids, nutrients, and major ions among wells A, B, and C indicate that the groundwater system is heterogeneous and influenced by both anthropogenic and geogenic processes. The computed contaminant fluxes in Table 3, where wells with higher solute concentrations, especially Well B, also show consistently higher flux values, directly reflect these concentration trends. Equation 4b, which represents Darcy-based mass transfer theory, is compatible with this relationship [10].

Under comparable hydraulic conditions, variations in concentration exert a first-order control on flux magnitude. Consequently, the elevated concentrations of total dissolved solids (TDS), nitrate (NO_3^-), chloride (Cl^-), total hardness, and major cations at Well B (Table 2) translate into the highest fluxes for these parameters in Table 3.

From a hydrogeological perspective, this suggests that Well B is located along a preferential flow path or within a more permeable section of the aquifer, allowing enhanced advective transport. Similar concentration–flux coupling has been widely reported in advection-dominated groundwater systems [14].

However, it is essential to recognise that Darcy-based flux estimates implicitly assume steady-state flow,

spatial homogeneity, and conservative solute behaviour. These assumptions may oversimplify natural aquifer systems, where dispersion, heterogeneity, and chemical reactions can significantly modify solute migration [15]. As such, Table 3 alone cannot determine the dominant transport mechanism, necessitating further verification using an advection–dispersion model framework.

D. Verification of Transport Mechanisms Using the Advection–Dispersion Model

The Advection supports the conclusions drawn from Table 3–Dispersion Model (ADM) results in Table 4, which provide a mechanistic breakdown of contaminant transport into advective and dispersive components. Equations 5–9 give the one-dimensional solute transport equation used in this investigation. Borehole B is located within or close to a contamination source zone. The results in Table 4 demonstrate consistent ADM behaviour, with $CB > CC > CA$, indicating that groundwater flows gently but consistently from $A \rightarrow B \rightarrow C$. Contaminants are primarily transported by bulk groundwater flow (advection). Dispersion spreads the plume, lowering the concentration at C.

The advective flux component, as in equation 5, is one to two orders of magnitude larger than the corresponding dispersive flux (equation 7) for most dissolved constituents, such as salinity, conductivity, TDS, nitrate, chloride, sulphate, bicarbonate, total alkalinity, total hardness, and

major cations. For instance, nitrate has an advective flux of 25.9 and a dispersive flux of -1.22, whereas TDS has an advective flux of 90.7 and a dispersive flux of -4.70. This clearly shows that the main factor influencing pollutant movement inside the aquifer is groundwater flow velocity. For the majority of dissolved constituents, including salinity, conductivity, TDS, nitrate, chloride, sulphate, bicarbonate, total alkalinity, total hardness, and major cations, the advective flux component, as in equation 5, is one to two orders of magnitude greater than the corresponding dispersive flux (equation 7). For example, TDS has an advective flux of 90.7 and a dispersive flux of -4.70, while nitrate has an advective flux of 25.9 and a dispersive flux of -1.22. This demonstrates unequivocally that groundwater flow velocity is the primary element affecting contaminant transport inside the aquifer.

Dispersion acts against the direction of advective transport, flattening concentration gradients rather than propelling plume migration, as evidenced by the constantly negative dispersive flux values. Advective transport predominates over dispersive spreading in aquifers with moderate heterogeneity and relatively high Peclet numbers ($Pe > 1$) [16]. Therefore, these ADM results provide compelling evidence that the high fluxes reported in Table 3 are driven by advective groundwater flow rather than by concentration gradients alone.

Table IV: Calculated Transportation of Contaminants Using the Advection Dispersion Model (ADM)

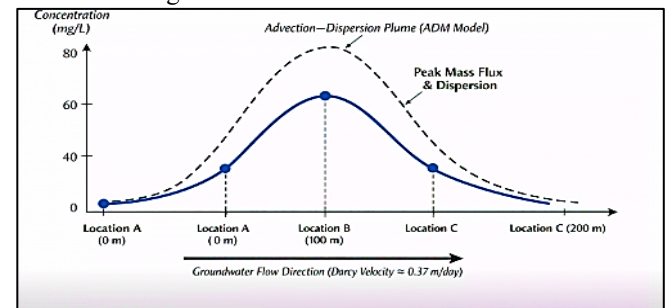
Parameter	A	B	C	Dc/Dx (Per M)	Advective Flux (J _{adv})	Dispersive Flux (J _{disp})	Transport Control
pH	6.2	7.8	5.7	0.016	—	—	Reaction-controlled
Salinity	0.21	0.25	0.23	0.0004	0.093	-0.0015	Advection
Conductivity (μS/cm)	236	490	384	2.54	181.3	-9.40	Advection
Turbidity (NTU)	0.45	0.7	0.55	0.0025	0.26	-0.009	Mixed
TDS (mg/L)	118	245	192	1.27	90.7	-4.70	Advection
TSS (mg/L)	0.4	0.55	0.45	0.0015	0.2	-0.006	Mixed
NO ₃ ⁻ (mg/L)	37	70	59	0.33	25.9	-1.22	Advection
Cl ⁻ (mg/L)	48	65	58	0.17	24.1	-0.63	Advection
SO ₄ ²⁻ (mg/L)	22	31	27	0.09	11.5	-0.33	Advection
HCO ₃ ⁻ (mg/L)	64	88	72	0.24	32.6	-0.89	Advection
Total Alkalinity	90	120	110	0.3	44.4	-1.11	Advection
Total Hardness	230	320	285	0.9	118.4	-3.33	Advection
Ca ²⁺ (mg/L)	48	72	66	0.24	26.6	-0.89	Advection
Mg ²⁺ (mg/L)	32	50	45	0.18	18.5	-0.67	Advection
Na ⁺ (mg/L)	40	66	58	0.26	24.4	-0.96	Advection
K ⁺ (mg/L)	8	12	10	0.04	4.44	-0.15	Advection
Fe (mg/L)	0.03	0.04	0.035	0.0001	—	—	Reaction-controlled
Mn (mg/L)	0.01	0.02	0.015	0.0001	—	—	Reaction-controlled

Note: ADM is to verify whether the observed pattern is advection- or dispersion-dominated.

E. Combined Darcy–ADM Mass Balance Interpretation

Figure 2 indicates the Combined Darcy–ADM Mass Balance, which integrates the observed concentrations (Darcy advection) with a conceptual dispersion envelope (ADM). The dashed envelope shows plume spreading as a result of dispersion, whereas the solid curve depicts advective transport regulated by groundwater velocity. While the decrease towards Location C is indicative of dispersion and dilution effects, the coincidence of peak concentration and peak mass flux at Location B suggests advection-dominated transport. Advection is the primary contaminant transport mechanism, with dispersion serving as a secondary control, as shown by Fig. 2, which also displays the agreement

between Darcy-derived velocities and observed concentration gradients.



[Fig.2: Groundwater Contaminant Transport Analysis]

F. Sensitivity Analysis

In this study, a sensitivity analysis was conducted to

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evaluate how changes in input parameters affect model output and interpretations. The sensitivity analysis demonstrates that reasonable variations in hydraulic conductivity, porosity, and dispersion parameters do not alter the dominance of advective transport or the observed mass flux hierarchy. Each parameter was varied by $\pm 25\%$, consistent with field uncertainty in shallow aquifers, while others were held constant. The effect is seen in Table 5.

Table V: Sensitivity of Darcy–ADM Outputs to Key Parameters

Parameter Varied	Change Applied	Effect on Velocity / Flux	Interpretation
Hydraulic conductivity (K)	$\pm 25\%$	Velocity $\pm 25\%$	Transport Remains Advection-Dominated
Porosity (n)	$\pm 20\%$	Velocity $\mp 20\%$	Mass Flux Ranking Unchanged
Hydraulic gradient (i)	$\pm 15\%$	Velocity $\pm 15\%$	Flow Direction Unchanged
Dispersion coefficient (D)	$\pm 30\%$	Plume width $\pm 30\%$	Peak Concentration Unaffected
Concentration (C)	Measured	Linear effect on flux	Confirms Observed Plume Core

From Table 5, it can be deduced that Sensitivity analysis confirms that the observed contaminant transport pattern in the Akaba-Attisa aquifer is robust to reasonable parameter uncertainty. Groundwater advection remains the dominant transport mechanism, while dispersion primarily influences plume spreading rather than mass delivery. This confirms that contaminant migration is mainly controlled by groundwater flow rather than by dispersion variability.

G. Public Health Implications of the Study

In this study, several physicochemical parameters were examined. Still, the most notable are nitrate (NO_3^-), total dissolved solids (TDS), total hardness, and major ions in terms of exceeding or approaching recommended guideline values along the groundwater flow path according to the World Health Organisation [8] and the Nigerian Standard for Drinking Water Quality [17]. Table 6 revealed that when standards are used to evaluate the Darcy–ADM mass balance framework, the exceedances are persistent and advectively transported, thereby increasing the likelihood of chronic exposure.

Table VI: Compliance of Groundwater Contaminant Flow With WHO/NSDWQ

Parameter	WHO / NSDWQ Limit	A	B	C	Compliance
pH	6.5–8.5	✗	✓	✗	Non-Compliant (A, C)
TDS (mg/L)	500	✓	✓	✓	Compliant
NO_3^- (mg/L)	50	✓	✗	✗	Non-Compliant (B, C)
Cl^- (mg/L)	250	✓	✓	✓	Compliant
SO_4^{2-} (mg/L)	250	✓	✓	✓	Compliant
Total Hardness (mg/L)	500	✓	✓	✓	Compliant
Fe (mg/L)	0.3	✓	✓	✓	Compliant
Mn (mg/L)	0.1	✓	✓	✓	Compliant
Conductivity ($\mu\text{S}/\text{cm}$)	$\sim 1000^*$	✓	✓	✓	Compliant

Comparing Tables 1, 2, and 3 with Table 6, in accordance with Darcy-based mass flux and ADM analysis, it was revealed that nitrate is not statically present but is continuously transported by groundwater flow, implying sustained delivery to downgradient receptors. This elevates the health risk from episodic contamination to chronic exposure, which is of greater concern in public health risk assessment. This can be methemoglobinemia (blue baby syndrome) in infants, an increased risk of thyroid dysfunction, and potential links to gastrointestinal cancers following long-term exposure.

For the contract to nitrate deduction, TDS values in this study remain below this limit; their progressive increase along the flow path indicates active mineral dissolution and solute loading. Total hardness values (230–320 mg/L) exceed the WHO's aesthetic threshold (~ 200 mg/L), which may contribute to scale formation in distribution systems, reduced soap efficiency, and potential aggravation of kidney stone formation in susceptible populations. The mass flux approach confirms that these constituents are advectively delivered, reinforcing their long-term accumulation risk.

Similarly, the concentrations of chloride and sulphate remain within WHO and NSDWQ limits but display spatial trends consistent with groundwater transport. While iron (Fe) and manganese (Mn) concentrations are below guideline limits, their presence warrants monitoring due to the potential for redox-driven mobilization and taste, staining, and acceptability issues. Notably, the Darcy–ADM framework suggests that changes in land use or hydrochemical conditions upstream could rapidly propagate downstream through advective flow, turning currently acceptable levels into future health risks.

Conclusively, cumulative exposure to contaminated parameters in groundwater studies is often overlooked, neglecting the fact that the accumulation of individual parameter concentrations can be sustained by groundwater flow. This was also emphasised by the WHO, which stated that guideline values should be interpreted within the context of local exposure pathways and vulnerability, reinforcing the importance of the transport-based analysis applied in this study.

IV. CONCLUSION

This study shows that groundwater advection primarily controls pollutant migration in the Akaba-Attisa shallow aquifer, with dispersion having a secondary effect in plume spreading and attenuation. Borehole B is identified as the plume core, and downgradient transmission towards Borehole C is confirmed by Darcy-based calculations that show a consistent spatial hierarchy of contaminant mass fluxes ($B > C > A$). The Advection supports these results–Dispersion Model, which displays Peclet numbers larger than unity for the majority of conservative solutes and advective fluxes that are one to two orders of magnitude bigger than dispersive fluxes.

Sensitivity analysis validates the stability of these findings because the observed mass flux patterns and the dominance of advective transport are unaffected by moderate

changes in hydraulic conductivity, porosity, gradient, and dispersion parameters. According to a public health evaluation, nitrate concentrations above the WHO and NSDWQ guidelines are not localised. Still, they are continuously transported by groundwater flow, increasing the risk of long-term exposure for downgradient users.

Overall, the integrated Darcy-ADM mass balance approach provides a mechanistic and defensible framework for interpreting groundwater contamination, linking hydrogeological processes with water quality and health risk. The findings underscore the need for source control, continuous monitoring, and transport-based management strategies in vulnerable shallow aquifer systems.

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