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Experimental and Numerical Modelling of Transport and Retention Dynamics of Kerosene in Ikot Abasi Soil after a Spill.

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Abstract - Kerosene spills in the Niger Delta region pose acute threats to soil integrity, groundwater quality, and public health, yet the site-specific fate of kerosene in the region's characteristic silt-clay soils remains poorly quantified. This study investigated the transport and retention behaviour of kerosene in Ikot Abasi soil under controlled laboratory conditions, employing column experiments with varying spill volumes (50 mL, 225 mL, and 400 mL) and simulated rainfall intensities (5, 7.5, and 10 mm/hr). Soil samples were characterised for particle size distribution, bulk density, porosity, organic matter content, and permeability. Total petroleum hydrocarbon (TPH) concentrations were quantified using gas chromatography with flame ionisation detection (GC-FID), and a Response Surface Method (RSM) based quadratic regression model was developed and validated to simulate kerosene transport and retention within a 30 cm soil profile. The soil exhibited silty-clay texture with bulk density of 1.861 g/cm³, low porosity (18.59%), and high organic matter (15.13%), properties that promote near surface retention under low rainfall. Transported TPH concentrations ranged from 80.79 mg/L to 20,480.80 mg/L. Peak transport occurred at 7.5 mm/hr rainfall intensity with 225 mL spill volume, revealing a non-linear optimum infiltration threshold beyond which dilution effects reduce leachate concentrations. Retention decreased with increasing rainfall intensity, confirming an inverse hydraulic-sorption relationship. The retention model demonstrated strong predictive accuracy ($R^2 = 0.9858$; $Q^2 = 0.8275$), while the transport model captured overall trends ($R^2 = 0.7893$). These findings provide a quantitative, site-specific basis for environmental risk assessment and remediation planning in oil producing communities of the Niger Delta.

Keywords: Kerosene transport, hydrocarbon retention, Total Petroleum Hydrocarbons (TPH), numerical modelling, rainfall intensity, Response Surface Method, Ikot Abasi Soil.

1.0 INTRODUCTION

The Niger Delta ecosystem is among the most ecologically fragile and pollution burdened environments globally. Decades of hydrocarbon extraction, pipeline failures, equipment malfunction, and deliberate sabotage have subjected the region's soils, surface waters, and groundwater systems to persistent and escalating contamination (Amnesty International, 2011; Orimoogunje et al., 2020). Kerosene, a widely used petroleum distillate in cooking, heating, and lighting across rural Nigerian communities is a particularly concerning contaminant because of its frequent spillage and its capacity to migrate rapidly through the vadose zone into shallow groundwater aquifers (Osuji & Onojake, 2020).When kerosene is released onto soil, it rapidly infiltrates the soil matrix, altering physical and chemical soil properties, diminishing microbial activity, and reducing agricultural productivity (Essien et al., 2018). Contamination of groundwater through kerosene leaching is a grave public health concern in the Niger Delta, where boreholes and shallow wells constitute the primary drinking water source for millions of people (Uzoekwe & Onwuliri, 2011). The health consequences of kerosene exposure include dermatological irritations, respiratory dysfunction, gastrointestinal disorders, and elevated cancer risk, disproportionately affecting children, pregnant women, and immunocompromised individuals (Akinmoladun et al., 2010; Ordinioha & Brisibe, 2013).Beyond ecological and health impacts, the economic consequences of kerosene spills in the Niger Delta are profound. Contaminated farmland reduces agricultural yields and threatens food security, while the cost of remediation and ecosystem restoration constitutes a significant fiscal burden for local governments and communities already constrained by limited economic resources (Frynas, 2001; Idemudia, 2010; Watts, 2008). The combination of sandy, high-porosity soils, shallow water tables, and intense seasonal rainfall makes the region particularly susceptible to rapid contaminant migration (Ezechi et al., 2021), compounding both the severity and geographic extent of kerosene spill impacts.

Despite the well documented consequences of hydrocarbon spills in the Niger Delta, a critical knowledge gap persists regarding the site-specific fate of kerosene in the region's soils. Existing studies have looked at a review of historical trends, drivers and impacts (spatial and temporal analysis) of gasoline spills in the Niger Delta (Eton et al., 2026), while others largely addressed generic hydrocarbon transport in tropical soils or have focused on diesel and crude oil rather than kerosene (Akpan et al., 2021a; Akpan et al., 2021b; Petaba et al., 2022; Amie-Ogan et al., 2022b). The distinctive geotechnical properties of Niger Delta soils, including high sand content, moderate to high porosity, low cation exchange capacity, and limited organic matter in many sub-areas create transport and retention dynamics that cannot be reliably extrapolated from studies conducted elsewhere (Onyeka et al., 2023; Eze et al., 2022; Ikechukwu et al., 2021).Furthermore, most prior modelling attempts have treated transport and retention as separate processes, without adequately integrating their mutual interactions under varying hydrological and volumetric conditions (Osuji & Onojake, 2020). The absence of validated, site-calibrated numerical models for Ikot Abasi represents a significant impediment to evidence-based risk assessment, remediation planning, and regulatory enforcement (Uchegbu & Okeke, 2023).

This study addresses the identified gap through an integrated experimental and modelling approach applied specifically to Ikot Abasi soil in Akwa Ibom State, Nigeria. By combining controlled laboratory column experiments with a statistically robust Response Surface Method (RSM) quadratic regression framework, the study simultaneously characterises kerosene transport and retention dynamics under realistic combinations of rainfall intensity and spill volume, and develops validated predictive models suitable for environmental management applications. The specific objectives were: to characterise the physical and chemical properties of Ikot Abasi soil governing kerosene mobility; to quantify TPH transport and retention under varying experimental conditions through 30 cm soil columns; to develop and validate numerical regression models for predicting transported and retained kerosene concentrations; and to derive practical implications for kerosene spill management and remediation in Niger Delta communities.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Ikot Abasi Local Government Area of Akwa Ibom State, located in the Niger Delta region of southern Nigeria (approximately 40 km southeast of Uyo, the state capital). The area is bounded by the Opobo Creek to the south, the Qua Iboe River to the west, and the Imo River to the east, with an average elevation of 10–20 m above sea level (Umoh et al., 2021). The region experiences a tropical monsoon climate, with intense seasonal rainfall events that increase the risk of contaminant mobilisation from spill sites. Soils of Ikot Abasi are generally sandy and acidic, with low nutrient availability, rendering them vulnerable to chemical contamination (Ita et al., 2023).

2.2 Soil Sample Collection and Characterisation

Undisturbed soil samples were collected from Ikot Abasi using an auger rig and preserved in airtight containers. Soil properties determined using standard laboratory methods included: particle size distribution (PSD) by the hydrometer method; bulk density and porosity by the soil core method; permeability by the constant head method; and organic matter content by the Walkley-Black method. GC-FID baseline analysis of water and soil samples prior to spill experiments confirmed the absence of detectable hydrocarbon residues.

2.3 Kerosene Characterisation

Kerosene samples sourced from Ikot Abasi were characterised for hydrocarbon composition using GC-FID analysis covering fractions from C8 to C40. Physical properties including density (hydrometer method), viscosity (viscometer method), and water solubility (shake flask method) were also determined. Total TPH content of the kerosene was confirmed at 23,094.6 mg/L.

2.4 Rainfall Simulator and Lysimeter Design

A rainfall simulator was locally fabricated using stainless steel, aluminium, and PVC components, capable of generating rainfall intensities between 5 and 100 mm/hr, consistent with ISO standard specifications. A mesocosm lysimeter was constructed to collect leachate from the soil column and quantify transported contaminant concentrations. The fabricated equipment was calibrated against an ISO-standard rainfall simulator and validated for intensity uniformity and leachate collection accuracy.

2.5 Experimental Design

The experimental design followed an RSM framework implemented in Excel Stat, employing a 3×3 full factorial arrangement with nine experimental runs. The independent variables were: contaminant volume (Cv: 50, 225, and 400 mL) and rainfall intensity (RI: 5, 7.5, and 10 mm/hr). The dependent variables were transported TPH concentration (TC, mg/L) and retained TPH concentration (RC, mg/kg) in a 30 cm soil column. Leachate samples collected from the base of the lysimeter were analysed for TPH using GC-FID, and post-simulation soil samples were extracted at 30 cm depth for retained TPH analysis.

2.6 Numerical Model Development, Calibration, and Validation

The transport and retention of kerosene in the soil were conceptualised using the advective-dispersive transport framework, incorporating advection ($V = -K \times dh/dl$), mechanical dispersion ($D = \alpha \times V$), and adsorption ($Q = Kd \times C$), where K is hydraulic conductivity, dh/dl is the hydraulic gradient, α is dispersivity, and Kd is the distribution coefficient (Akpan et al., 2022a; Akinola et al., 2023). Quadratic regression models were developed using the RSM Excel Stat tool. Model performance was evaluated using RMSE, R^2, and Nash-Sutcliffe Efficiency (NSE).

3.0 RESULTS AND DISCUSSION

3.1 Soil Characterisation

The Ikot Abasi soil was classified as silty-clay with a particle size distribution of 0.075–2.4 mm. Table 1 presents the principal geotechnical characteristics. Bulk density was 1.861 g/cm³ and particle density 2.286 g/cm³, yielding a porosity of 18.59%. The organic matter content of 15.13% is notably high and consistent with the alluvial and marshy conditions of the Niger Delta (Orimoogunje et al., 2020). The low porosity and fine texture of the soil limit deep vertical migration of contaminants, concentrating hydrophobic hydrocarbons like kerosene near the surface.

Table 1: Physical and chemical characteristics of Ikot Abasi soil

Soil Type	PSD (mm)	Particle Density (g/cm³)	Bulk Density (g/cm³)	Porosity	Organic Matter (%)
Silt-Clay	0.075–2.4	2.286	1.861	0.1859	15.13

(Author’s compilation)

These soil properties have significant implications for kerosene behaviour. The high organic matter content enhances hydrophobic sorption of kerosene fractions, promoting surface retention under low rainfall conditions. Conversely, the moderate permeability creates conditions under which elevated rainfall can exceed the soil's sorptive capacity, promoting deeper percolation and leachate transport.

3.2 Kerosene Hydrocarbon Composition (GC-FID Analysis)

The GC-FID analysis confirmed a complex hydrocarbon composition spanning C8 to C40 (Table 2), with total TPH of 23,094.6 mg/L. Dominant fractions were C33 (5,738.4 mg/L), C17 (4,595.3 mg/L), C35 (2,871.9 mg/L), and Pristane (2,537.7 mg/L). The wide carbon chain range indicates markedly different mobility, sorption, and biodegradation characteristics across fractions. Figure 1 (GC-FID profile) illustrates the full compositional distribution. Lighter fractions (C8–C12) contribute to rapid initial mobilisation, while heavier fractions (C27–C40) exhibit stronger sorption to organic matter and clay particles, contributing to long-term retention.

Table 2: Selected Hydrocarbon Fractions Identified by GC-FID Analysis (Ikot Abasi Kerosene Sample)

Hydrocarbon Component	Petroleum Product Conc. (mg/L)	Water/Soil Baseline (mg/L or mg/kg)
C8	649.74	ND
C12	1,314.82	ND
C17	4,595.30	ND
Pristane	2,537.67	ND
C18	1,890.14	ND
Phytane	886.87	ND
C33	5,738.38	ND
C35	2,871.91	ND
Total TPH	23,094.60	0.00

ND = Not Detected

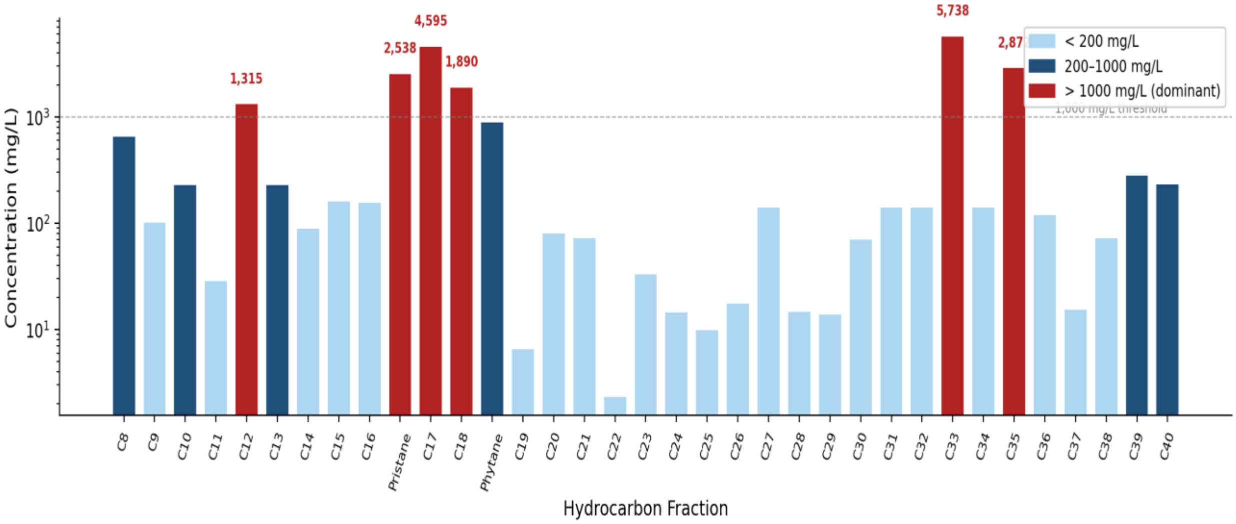

Figure 1: GC-FID Hydrocarbon Composition Profile of Ikot Abasi Kerosene Sample (C8–C40 fractions; Total TPH = 23,094.6 mg/L)

The bar chart displays individual hydrocarbon fraction concentrations on a logarithmic scale. Colour coding distinguishes dominant fractions (red, >1,000 mg/L) from intermediate (dark blue, 200–1,000 mg/L) and minor fractions (light blue, <200 mg/L). The five dominant fractions: C33 (5,738 mg/L), C17 (4,595 mg/L), C35 (2,872 mg/L), Pristane (2,538 mg/L), and C18 (1,890 mg/L) account for the majority of total TPH and govern the sorption and mobility behaviour of the kerosene in soil. Lighter fractions (C8–C12) are more volatile and mobile, while heavier fractions (C27–C40) exhibit stronger affinity to soil organic matter, contributing disproportionately to long term retention.

3.3 Overview of Experimental TPH Results

Transported and retained TPH concentrations across all nine experimental runs are summarised in Table 3 and illustrated in Figure 2. Transported TPH ranged from 80.79 mg/L to 20,480.80 mg/L, while retained TPH ranged from 10.01 mg/kg to 32.36 mg/kg, a range spanning nearly three orders of magnitude in the transport variable, underscoring the high sensitivity of kerosene mobility to both spill volume and rainfall intensity.

Table 3. Observed Transported and Retained TPH Concentrations under Varying Experimental Conditions

Obs.	Spill Volume (mL)	Rainfall Intensity (mm/hr)	Retained TPH (mg/kg)	Transported TPH (mg/L)
1	50	5	18.23	84.93
2	225	5	25.23	80.79
3	400	5	32.36	11,985.76
4	50	7.5	15.21	1,299.05
5	225	7.5	16.88	20,480.80
6	400	7.5	30.93	19,256.10
7	50	10	10.01	1,261.00
8	225	10	11.22	1,269.26
9	400	10	24.48	20,115.60

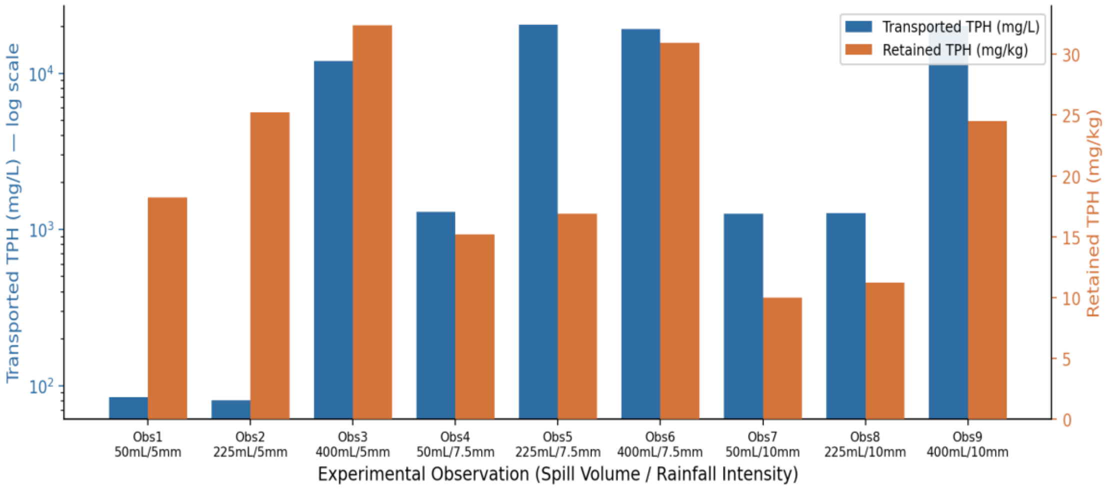

Figure 2: Transported (mg/L, log scale) and Retained (mg/kg) TPH Concentrations Across Nine Experimental Conditions

The plot highlights that transported concentrations span nearly three orders of magnitude (80.79–20,480.80 mg/L), while retained concentrations vary within a narrower range (10.01–32.36 mg/kg). Observations 5 and 9 (225 mL and 400 mL at 7.5 mm/hr) produced the highest transport values, while Observation 3 (400 mL at 5 mm/hr) yielded peak retention, illustrating the inverse relationship between rainfall driven transport and near surface retention**.**

3.4 Kerosene Transport Dynamics

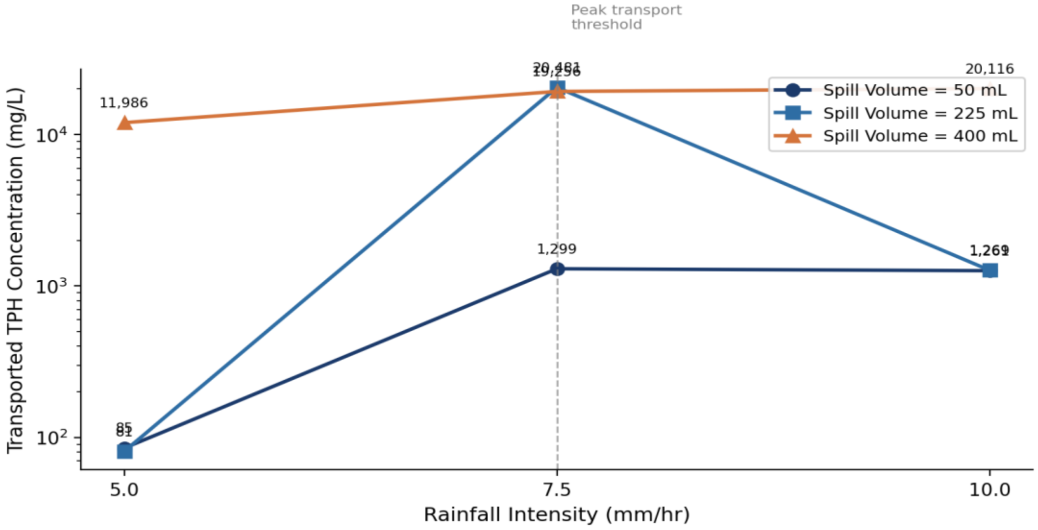

Figure 3: Effect of Rainfall Intensity on Transported TPH Concentration at Varying Spill Volumes (log scale; dashed line marks peak transport threshold at 7.5 mm/hr)

The line charts in Figure 3 illustrate the effect of rainfall intensity on transported TPH concentration at each spill volume level. Each line represents a fixed spill volume (50, 225, and 400 mL) tracked across rainfall intensities of 5, 7.5, and 10 mm/hr. A critical non-linear behaviour is evident in the 225 mL series: transported TPH surged from 80.79 mg/L at 5 mm/hr to a peak of 20,480.80 mg/L at 7.5 mm/hr, then fell sharply to 1,269.26 mg/L at 10 mm/hr. The dashed vertical line at 7.5 mm/hr marks this optimal infiltration threshold, beyond which increased hydraulic gradient and dilution effects suppress leachate TPH concentrations. The 400 mL series remained high across all intensities, reflecting the dominant role of spill volume in sustaining transport even under dilution. The 50 mL series showed uniformly low transport, confirming that small spills are largely retained in Ikot Abasi's silty-clay topsoil under all tested rainfall conditions. This finding has important practical implications in that, post-spill irrigation management must be carefully calibrated, as excessive rainfall simulation could paradoxically reduce surface-zone leachate concentrations while enabling deeper aquifer penetration.

3.5 Kerosene Retention Dynamics

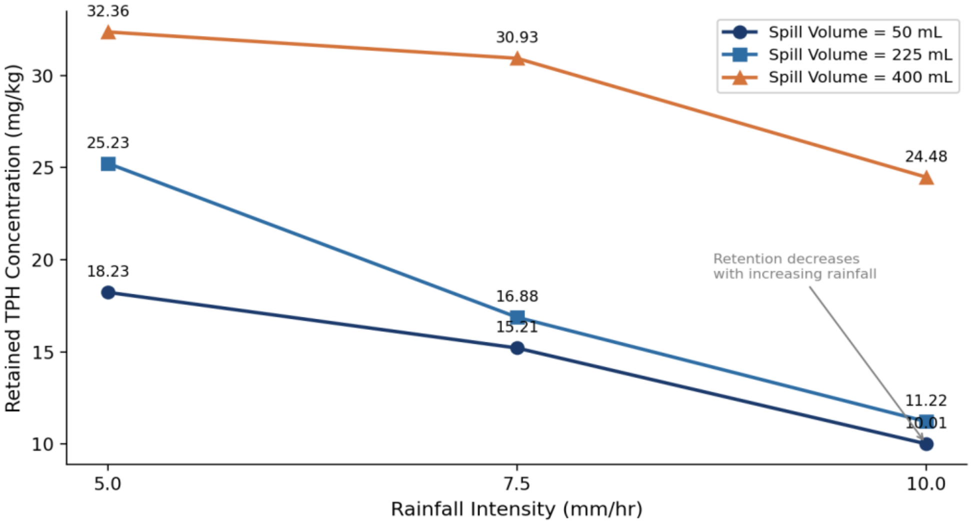

Figure 4: Effect of Rainfall Intensity on Retained TPH Concentration at Varying Spill Volumes

Figure 4 presents the effect of rainfall intensity on retained TPH across the three spill volumes. Retained concentrations ranged from 10.01 mg/kg to 32.36 mg/kg, displaying a direct positive correlation with spill volume and an inverse relationship with rainfall intensity. Retention declined as rainfall intensity increased, confirming that higher hydraulic gradients reduce contact time between kerosene and soil particles, thereby limiting adsorption capacity. This inverse relationship is consistent with advective dispersive transport theory: as the hydraulic gradient increases, the advective component dominates over diffusion and adsorption, flushing kerosene deeper into the profile and reducing the fraction retained in topsoil (Akinola et al., 2023; Gbinu et al., 2022). The high organic matter content (15.13%) of Ikot Abasi soil partially moderates this effect by providing additional hydrophobic binding sites, particularly for the heavier C27–C40 fractions.

At low rainfall intensity (5 mm/hr), longer soil kerosene contact time allows hydrophobic sorption of kerosene fractions onto organic matter and clay particles, yielding higher retention values of up to 32.36 mg/kg (400 mL series). As rainfall intensity increases to 10 mm/hr, the advective force dominates, flushing kerosene downward and reducing topsoil retention to a minimum of 10.01 mg/kg (50 mL series). The consistently higher retention of the 400 mL series across all rainfall levels confirms that larger spill volumes saturate the soil’s sorptive capacity, resulting in measurably higher residual concentrations even under high hydraulic gradients.

These retention dynamics have direct implications for remediation design. In dry-season conditions which prevail in Ikot Abasi during (November–March), kerosene accumulates significantly in the topsoil zone, making in-situ soil amendment strategies including sorptive additive incorporation and phytoremediation viable options. During the wet season, reduced retention and increased transport necessitate groundwater monitoring and potential installation of subsurface barriers.

3.6 Relationship between Transported and Retained TPH Concentrations

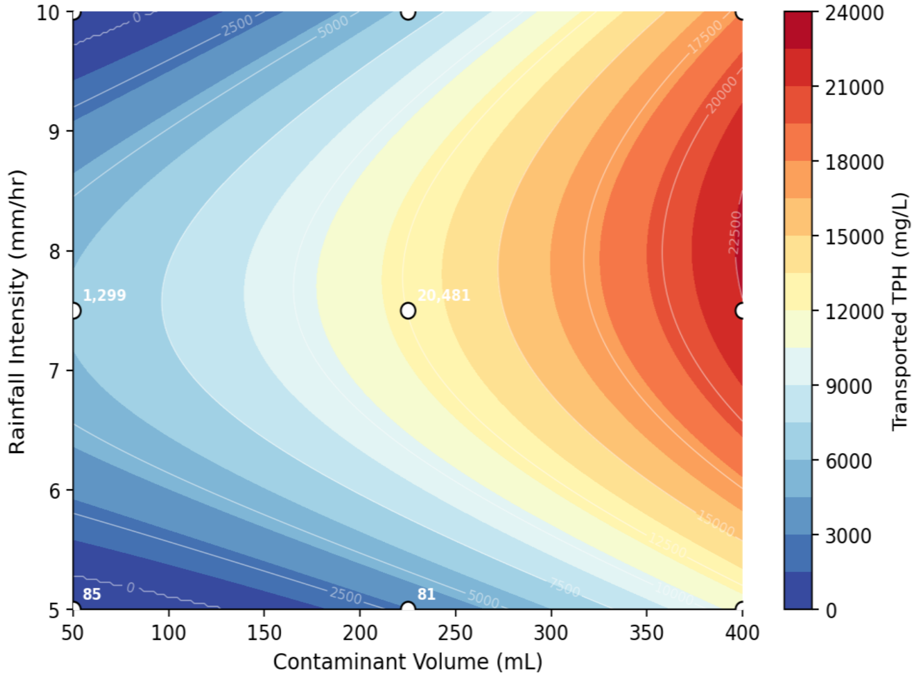

Figure 5: 2D Contour Plot of Transported TPH Concentration (mg/L) as a Function of Spill Volume and Rainfall Intensity (observed data points shown as white circles)

Figures 5 and 6 illustrates 2D contour plots of transported and retained TPH concentrations as functions of spill volume and rainfall intensity. In Figure 5, the red zone indicating maximum transported concentrations is concentrated around moderate rainfall (7.5 mm/hr) and mid to high spill volumes (225–400 mL), confirming the non-linear transport optimum. Figure 6 shows that peak retention occurs at high spill volumes combined with low rainfall intensity (lower-right region), with retention diminishing progressively toward the upper portion of the rainfall axis.

The RSM quadratic transport model (Equation 1) is used to interpolate the response surface continuously across the experimental design space. The red zone, indicating peak transported TPH exceeding 20,000 mg/L, is concentrated around moderate rainfall (7.0–8.5 mm/hr) combined with intermediate to high spill volumes (200–400 mL), confirming the non-linear transport optimum identified experimentally. Cool blue regions at the periphery represent low-transport zones, particularly under low rainfall and small spill volumes. White circles denote the nine observed data points; the close correspondence between observed values and the modelled surface contours validates the predictive capability of the RSM model at lower to mid-range TPH concentrations, although the model underestimates peak values at 7.5 mm/hr.

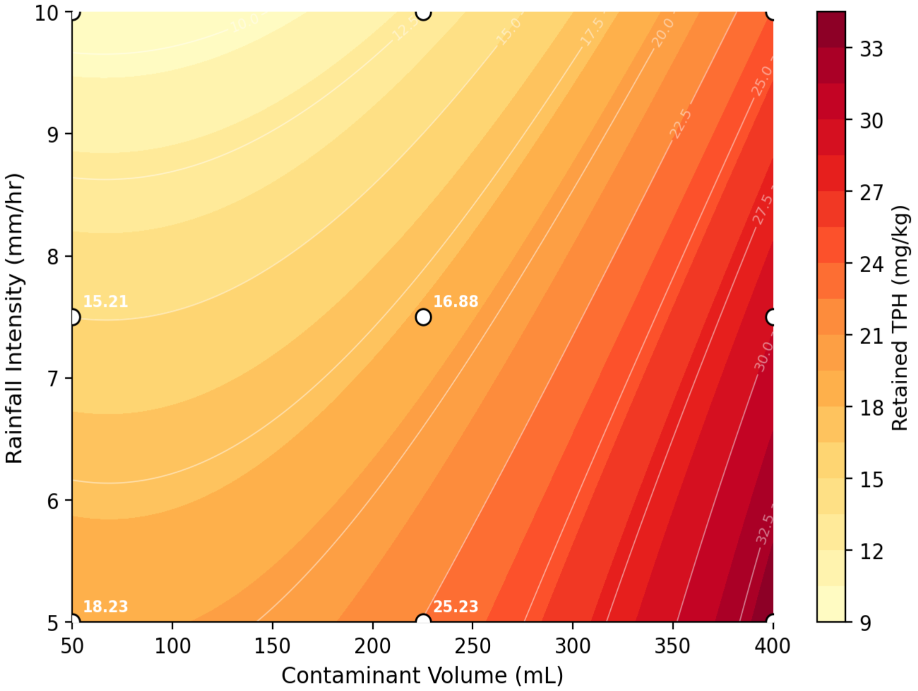

Figure 6: 2D Contour Plot of Retained TPH Concentration (mg/kg) as a Function of Spill Volume and Rainfall Intensity (observed data points shown as white circles)

The RSM quadratic retention model (Equation 2) generates a well-behaved, monotonically varying surface across the design space. Peak retention (dark red, >30 mg/kg) occupies the lower-right region of the plot, corresponding to high spill volumes (350–400 mL) and low rainfall intensity (5–5.5 mm/hr). Moving upward along the rainfall axis reduces retention progressively, producing a gradient from red through orange to light yellow in the upper-left corner. This orderly pattern, consistent with the high model R^2 (0.9858) and Q^2 (0.8275), reflects the dominant and additive influence of both spill volume and rainfall intensity on retention, with no saddle point or complex interaction, unlike the transport surface. The close agreement between white observed data points and surrounding contour values confirms the strong predictive accuracy of the retention model. The three-dimensional response surfaces in Figures 7 and 8 provide additional spatial clarity on these relationships. The transport surface (Figure 7) exhibits a pronounced curvature along the rainfall intensity axis, with the saddle shape reflecting the non-linear transport behaviour. The retention surface (Figure 8) shows a monotonically declining gradient with increasing rainfall at all spill volume levels, while rising steeply with increasing contaminant volume, confirming the dominant role of spill volume in governing retention.

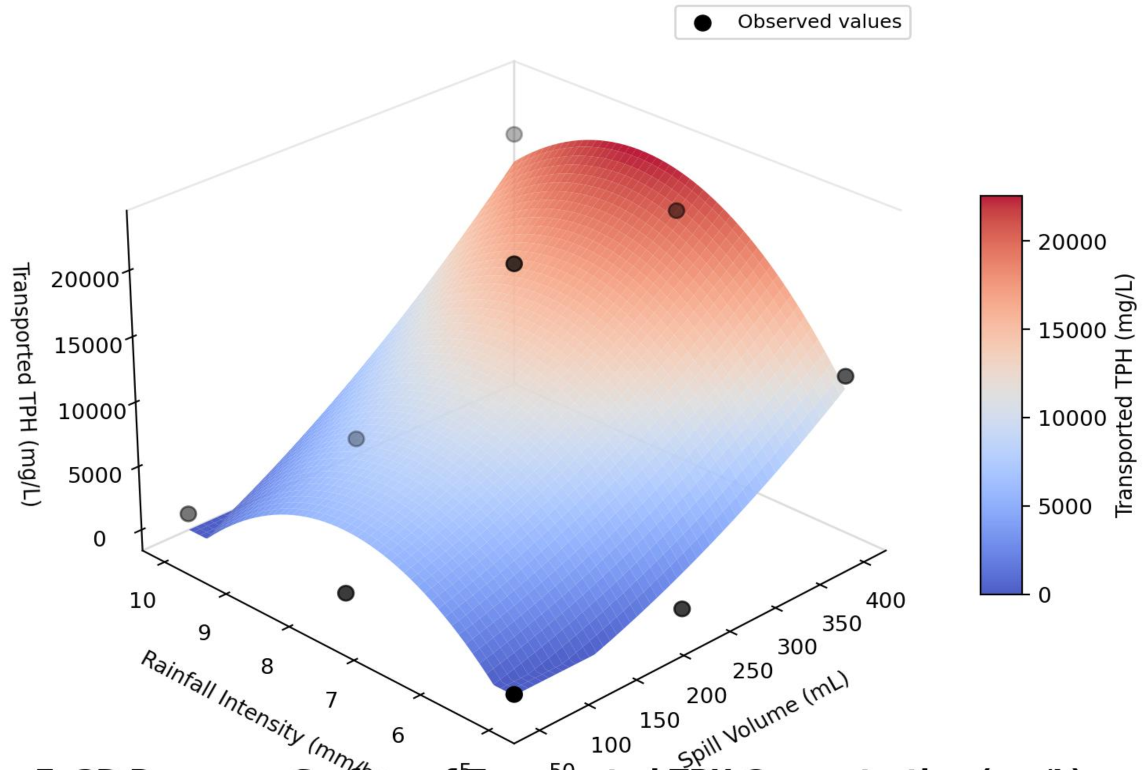

Figure 7: 3D Response Surface of Transported TPH Concentration (mg/L) Derived from the RSM Quadratic Transport Model (Equation 1)

The cool-toned (blue) base of the surface at low rainfall and small volumes contrasts sharply with the warm-toned (red) apex, highlighting the concentration gradient across the experimental domain. Black dots representing observed data points follow the general topography of the modelled surface, though some scatter at peak values is consistent with the model's moderate R^2 of 0.7893 and negative Q^2, indicating that the second-order polynomial cannot fully resolve the sharp non-linear spike at 7.5 mm/hr. The saddle-shaped depression visible at high rainfall and low-to-mid spill volumes is a mathematical artefact of the quadratic formulation and not a physical phenomenon.

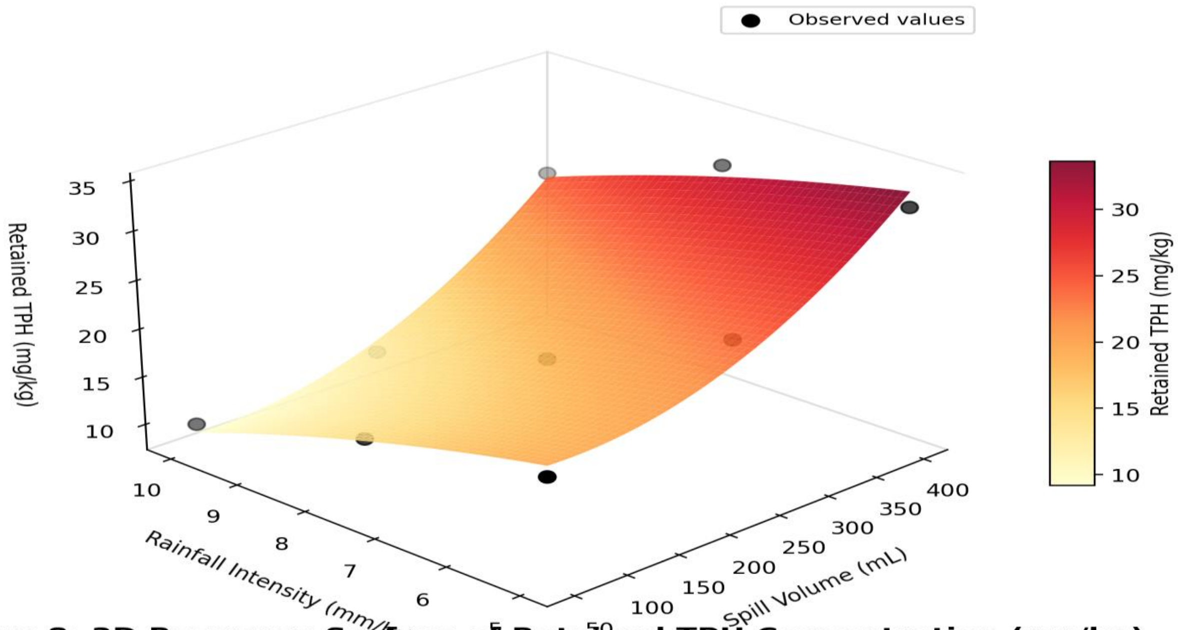

Figure 8: 3D Response Surface of Retained TPH Concentration (mg/kg) Derived from the RSM Quadratic Retention Model (Equation 2)

Unlike the transport surface, the retention surface is smooth, well-defined, and monotonically varying: it rises steeply from the low-volume, high-rainfall corner (minimum ~10 mg/kg) to the high-volume, low-rainfall corner (maximum ~35 mg/kg), with no inflection or saddle point. This smooth gradient reflects the physically consistent, additive relationship between spill volume and rainfall intensity on topsoil retention. The near-perfect alignment of observed black data points with the modelled surface confirms the superior fit of the retention model ($R^2 = 0.9858$; $Q^2 = 0.8275$) and underscores its suitability as a decision-support tool for site-specific risk assessment. The warm colour gradient from yellow (low retention) to deep red (high retention) reinforces the visual contrast between sorption-dominated and hydraulically flushed zones in Ikot Abasi soil.

3.7 Numerical Model Development and Validation

Two quadratic regression models were derived from the RSM analysis. The transported concentration model (Equation 1) and the retention concentration model (Equation 2) are:

$$TC = 12{,}530 + 8{,}119Cv + 1{,}749RI + 1{,}723Cv^2 - 7{,}879RI^2 + 1{,}738Cv \times RI \quad \dots (1)$$

$$RC = 18.281 + 7.388Cv - 5.018RI + 4.093Cv^2 - 0.754RI^2 + 0.086Cv \times RI \quad \dots (2)$$

where TC is transported TPH (mg/L), RC is retained TPH (mg/kg), Cv is contaminant volume (mL), and RI is rainfall intensity (mm/hr).

The retention model demonstrated excellent predictive performance ($R^2 = 0.9858$; $Q^2 = 0.8275$). The transport model captured directional trends ($R^2 = 0.7893$) but exhibited a negative (Q^2 of -0.6096), reflecting the high variance and non-linearity in observed transport data particularly the departure from monotonic behaviour at 7.5 mm/hr which a second-order polynomial cannot fully resolve (Amie-Ogan et al., 2022a; Petaba et al., 2022).

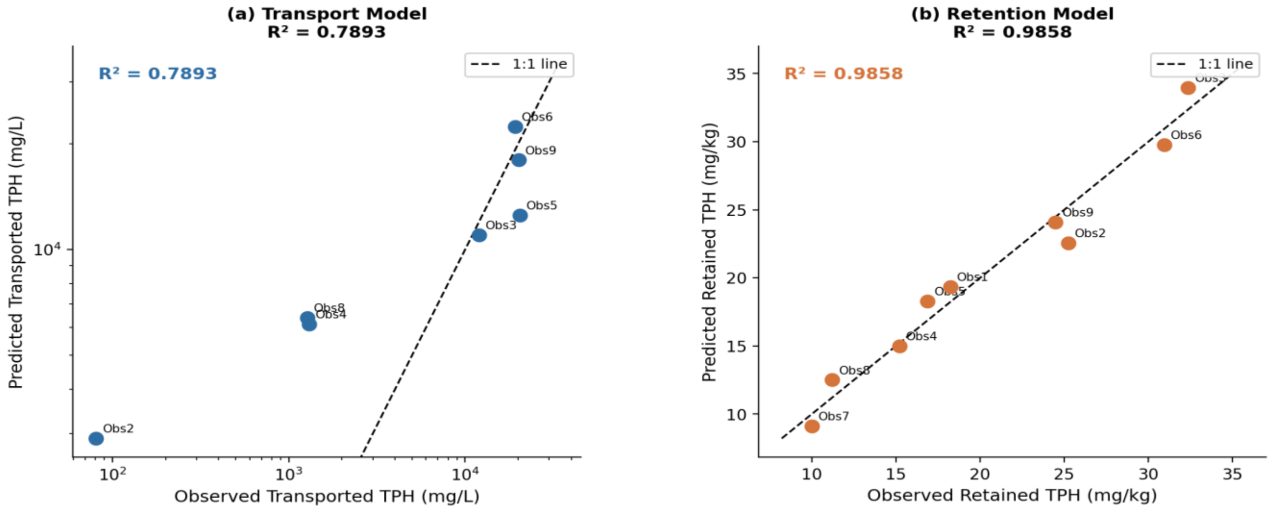

Figure 9: Observed vs. Predicted TPH Concentrations for Transport and Retention Models

In Figure 9(a), predicted transported TPH values are plotted against observed values on a log-log scale; the systematic overestimation at low concentrations and underestimation at high concentrations is reflected in the scatter of points away from the dashed 1:1 line, consistent with the model's negative Q^2 (-0.6096) and limited ability to resolve the sharp non-linear peak at 7.5 mm/hr. In Figure 9 (b), the retention model shows close clustering of all nine observations around the 1:1 line, confirming excellent predictive accuracy across the full range of retained concentrations (10–32 mg/kg). This contrast in model performance has practical implications: the retention model can be used directly for site-specific risk assessment and remediation planning, while the transport model provides directional trend guidance and requires supplementation with field-scale validation or higher-order modelling for accurate leachate concentration estimation.

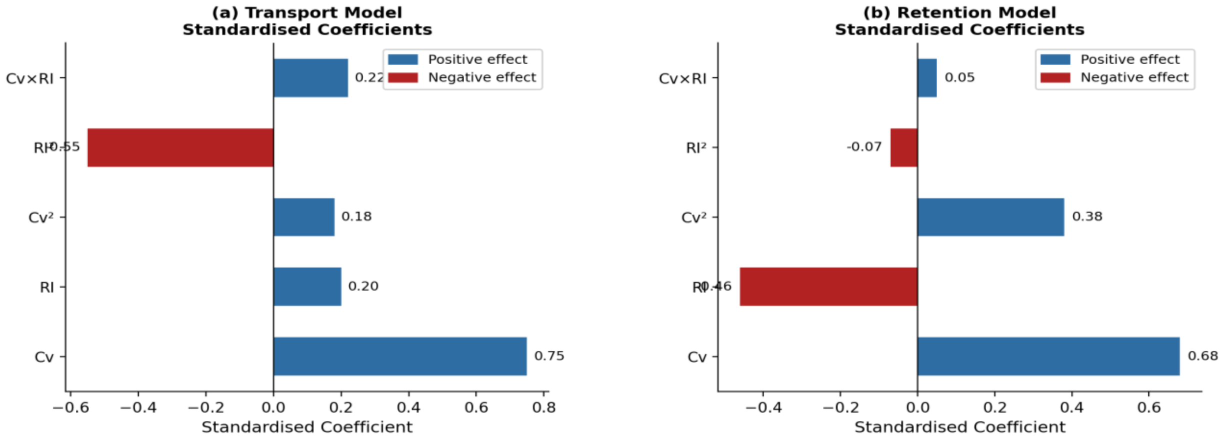

Figure 10: Standardised Regression Coefficients for the (a) Transport and (b) Retention RSM Models

Figure 10 illustrates Standardised Regression Coefficients for the (a) Transport and (b) Retention RSM Models. Standardised coefficients allow direct comparison of the relative influence of each model term, independent of measurement units. In the transport model (Figure10 a), contaminant volume (Cv) exerts the dominant positive influence (coefficient = 0.75), confirming that the volume of kerosene spilled is the single most important determinant of how much TPH reaches the base of the soil column. Rainfall intensity (RI) has a smaller positive linear effect (0.20), but its squared term (RI^2) has a large negative coefficient (−0.55), explaining the reversal of transport at 10 mm/hr. In the retention model (Figure 10b), Cv again dominates positively (0.68), while RI exerts a strong negative influence (−0.46), confirming that higher rainfall intensity suppresses topsoil retention. The Cv^2 term contributes positively (0.38), suggesting a non-linear amplification of retention at very high spill volumes. These findings collectively reinforce the practical recommendation that volumetric spill containment is the most effective single intervention for limiting kerosene migration in Ikot Abasi soil.

3.8 Environmental Management Implications

The integrated results provide a quantitative framework for evidence based environmental management of kerosene spills in Ikot Abasi and comparable Niger Delta environments. The validated retention model offers a reliable decision support tool that can simulate kerosene fate under site-specific weather and spill scenarios, enabling environmental managers to identify high-risk zones and optimise remediation interventions. Under dry-season conditions, kerosene accumulates near the soil surface, supporting deployment of topsoil focused strategies including bioremediation with indigenous microorganisms, sorptive additive incorporation and phytoremediation. During the wet season, when rainfall-driven transport increases groundwater contamination risk, proactive installation of passive containment barriers and real time groundwater monitoring are warranted. These findings reinforce calls for strengthened regulatory enforcement of spill prevention standards in the Nigerian oil and gas sector.

4.0 CONCLUSION

This study demonstrated through controlled laboratory experimentation and validated numerical modelling, that the transport and retention of kerosene in Ikot Abasi silt-clay soil are governed by a complex, non-linear interplay of spill volume, rainfall intensity, and soil physicochemical properties. Findings from the research indicates that physical and chemical characteristics of Ikot Abasi soil, notably its low porosity (18.59%), high organic matter content (15.13%), and silt-clay texture promote near-surface kerosene retention under low rainfall, while exposing the soil to rapid leachate transport under moderate to heavy rainfall.

Transported TPH concentrations ranged from 80.79 mg/L to 20,480.80 mg/L. Peak transport was observed at 7.5 mm/hr with 225 mL spill volume, revealing an optimal infiltration threshold beyond which dilution effects attenuate leachate concentrations. Retained TPH concentrations (10.01–32.36 mg/kg) showed a direct correlation with spill volume and an inverse relationship with rainfall intensity, confirming that hydraulic flushing reduces sorption capacity under high-gradient conditions. The RSM-derived retention model ($R^2 = 0.9858$; $Q^2 = 0.8275$) provides a reliable predictive tool for site-specific risk assessment, while the transport model ($R^2 = 0.7893$) captures directional trends adequate for early-stage environmental screening. Contaminant volume is the dominant predictor of kerosene transport (standardised coefficient = 0.75), highlighting volumetric spill containment as the most effective single intervention for limiting contaminant migration.

LIMITATIONS OF THE STUDY

This study is subject to several limitations:

- **Laboratory scale:** All experiments were conducted in 30 cm soil columns under controlled conditions. Natural field-scale variability in soil texture, stratification, macropore networks, and root channels may produce transport and retention behaviours not fully captured by column experiments.
- **Absence of groundwater interaction:** The experimental design did not incorporate a water table or simulate kerosene-groundwater interaction.
- **Biodegradation not modelled:** The RSM models do not incorporate temporal biodegradation kinetics.
- **No field-scale validation:** The absence of field data for model corroboration limits direct transferability of the findings to real-world spill scenarios without further validation studies.

RECOMMENDATIONS FOR FUTURE RESEARCH

- **Field-scale validation:** In-situ spill experiments and retrospective analysis of historical contamination sites in the Niger Delta are urgently needed to calibrate and validate laboratory-derived models under real-world conditions, accounting for natural soil heterogeneity, macropore flow, and seasonal hydrological variability.
- **Multiphase and reactive transport modelling:** Future models should integrate multiphase flow (kerosene–water–air), reactive geochemistry, and non-equilibrium transport to more accurately simulate contaminant fate in stratified and heterogeneous soil profiles. Probabilistic methods such as Monte Carlo simulations should be incorporated to address parameter uncertainty.
- **Biodegradation kinetics:** Longitudinal studies incorporating time-dependent hydrocarbon aging and microbial degradation under both aerobic and anaerobic conditions will improve model fidelity and support design of bioremediation programmes tailored to Niger Delta soil microbial consortia.
- **Comparative soil studies:** Extending the experimental framework to other Niger Delta soil types including sandy loam and alluvial clay soils will support development of generalised regional models applicable across the broader Niger Delta hydrocarbon-impacted zone.

CRediT Authorship Contribution Statement

Idara Eton: Conceptualization, Methodology, Investigation, Experimental design, Writing original draft; **Philip E. Philip & Nsikakabasi I. Bassey**: Data curation, Formal analysis, Numerical modelling, Validation; **Ephraim R. Afia**: Writing, Review & editing; **Paul Paulinus Akpan:** Investigation, Laboratory experimentation, Data collection; **Ediongsenyene U. Inock:** Visualization, Literature review, Writing, review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the results reported in this study.

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