

A Multi-Pathway Contamination Risk Model for Niger Delta Communities: Integrating Hydrocarbon Load, Heavy Metal Exposure, and Vegetation Stress Indices from Heterogeneous Observational Data

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Abstract

The Niger Delta is one of the most petroleum-impacted environments in the world, yet spatially explicit contamination risk assessments that integrate multiple exposure pathways remain scarce. This study presents a Composite Risk Score (CRS) model that fuses heavy metal soil and water measurements from nine peer-reviewed studies, total petroleum hydrocarbon (TPH) data from the 2011 UNEP Environmental Assessment of Ogoniland, 15,630 georeferenced oil spill incidents from the National Oil Spill Detection and Response Agency (NOSDRA), and pre/post-spill Sentinel-2 NDVI indices for 500 spill events. Two XGBoost models were trained on 106 georeferenced sample points to predict exceedance of established contamination thresholds across two spatially extrapolatable pathways: hydrocarbon load exceeding EGASPIN limits, and normalised heavy metal burden relative to WHO reference values. The human health pathway was characterised separately by computing a hazard index directly from measured concentrations at each sample point, following the USEPA oral ingestion framework, rather than by model prediction, since it cannot be extrapolated to ungauged locations without measurements. The two model outputs were combined into a single CRS through PCA-derived pathway weighting and spatially interpolated across a 1 km² grid covering Rivers, Bayelsa, Delta, Edo, Akwa Ibom, and Cross River States. The IDW-model blend ratio was optimised empirically via spatial leave-one-out cross-validation. The TPH exceedance classifier achieved a cross-validated AUC of 0.798 and the metal index regressor a cross-validated RMSE of 0.024. The interpolated risk surface identified 63 critical and 551 high-risk grid cells, concentrated in Ogoniland and the Warri-Escravos corridor. Sabotage-related spill density within 25 km explained the largest share of variance in the CRS, consistent with the predominantly anthropogenic contamination pattern documented in prior literature. The dataset and interactive risk map are publicly available at <https://github.com/Ojochogwu866/nd-public> and <https://research-map.ojochogwu.dev/>.

1. Introduction

The Niger Delta encompasses approximately 70,000 km² of wetland, mangrove, freshwater, and estuarine ecosystems across nine states of southern Nigeria, and has been the site of continuous petroleum extraction since commercial production began in 1958. Over the intervening decades, the region has absorbed one of the highest sustained densities of oil spill incidents recorded for any petroleum-producing jurisdiction in the world. The NOSDRA Oil Spill Monitor, which began systematic digital recording in 2006, documents more than 15,000 confirmed incidents through 2025, with approximately 78% attributable to sabotage or third-party interference with pipeline infrastructure. Beyond acute spill events, the cumulative legacy of decades of petroleum industry operations has produced chronic contamination of soil, surface water, groundwater, and marine sediment through produced water discharge, refinery effluent, gas flaring condensate deposition, and artisanal refining activities across the delta.

The health consequences of this contamination burden are documented across a large and growing body of peer-reviewed literature. Studies conducted in Rivers, Bayelsa, Delta, Edo, and Cross River States have consistently reported exceedances of WHO, NESREA, and FAO guideline values for lead, cadmium, arsenic, nickel, and total petroleum hydrocarbons in soil, drinking water, food crops, and fish tissue consumed by local communities (Okoye et al., 2022; Dimowo et al., 2025; Akinkpelumi et al., 2026; Musa et al., 2017). Hazard index values exceeding 1.0 for oral ingestion pathways have been reported in multiple communities, with cancer risk estimates for arsenic in food crops from pipeline right-of-way zones reaching 1.5 times the USEPA threshold of 1 in 10,000 in child population groups (Akinkpelumi et al., 2026). These findings establish a robust empirical basis for contamination-associated health risk characterisation in the region, but they remain largely fragmented by geography, measurement medium, and contaminant class.

The 2011 UNEP Environmental Assessment of Ogoniland constitutes the most comprehensive single-source environmental dataset produced for the Niger Delta to date. Covering more than 200 sites across the Ogoni area of Rivers State, the assessment documents soil TPH values exceeding 49,000 mg/kg at Ejama-Ebubu, groundwater TPH concentrations above 1,000,000 micrograms per litre at several borehole sites, and benzene contamination of community drinking water wells in excess of WHO limits by factors of up to 900. The assessment concluded that full remediation of affected soils and groundwater would require a minimum of 25 to 30 years under an intensive, well-funded programme. Despite the significance of these findings, the assessment is geographically confined to the Ogoni area, and its primary contamination metric, total petroleum hydrocarbons, does not directly capture the heavy metal burden arising from crude oil composition, refinery proximity, and pipeline corrosion, which is systematically characterised in a parallel body of peer-reviewed literature that the UNEP assessment does not synthesise.

Integrated spatial risk assessments that bring together multiple contaminant pathways, multiple data sources, and a continuous geographic extent across the Niger Delta remain absent from the published literature. Existing assessments are typically bounded to a single local government area or waterway, rely on a single contamination medium, and do not generate spatially continuous risk surfaces that would permit cross-site comparison or identification of inter-community risk gradients. This fragmentation constrains the ability of environmental regulators, development finance institutions, and affected communities to prioritise remediation resources, assess cumulative environmental liability, or evaluate the spatial relationship between contamination burden and community health outcomes at a regional scale. The due diligence frameworks applied

by international development finance institutions, including the IFC Performance Standards and the Equator Principles, require environmental risk characterisation that extends beyond individual site assessments to encompass the geographic footprint of operations; the absence of a regional multi-pathway risk surface makes this requirement difficult to satisfy with currently available data.

Machine learning approaches to environmental contamination risk assessment have been applied in a range of contexts, including soil heavy metal prediction from remote sensing covariates, groundwater quality classification, and oil spill trajectory modelling. Gradient-boosted decision tree methods, of which XGBoost is among the most widely used implementations, have demonstrated strong performance in geospatial prediction tasks characterised by mixed feature types, non-linear relationships, and moderate sample sizes, making them well-suited to the data characteristics of the Niger Delta contamination dataset. The integration of gradient-boosted classifiers with spatial interpolation has been applied in analogous contexts including agricultural soil nutrient mapping and urban air quality prediction, where the combination of model-derived predictions and measurement-anchored interpolation outperforms either approach used alone.

Remote sensing offers a complementary observational pathway that partially addresses the spatial coverage limitation of ground-based measurement campaigns. The Normalised Difference Vegetation Index computed from Sentinel-2 multispectral imagery, available at 10-metre resolution globally since 2015, provides a time-referenced indicator of vegetation condition that is sensitive to petroleum-related phytotoxic stress. Pre/post-spill NDVI comparison provides a time-referenced indicator of acute vegetation impact that is independent of the ground-based measurement dataset and can be extracted for large numbers of incidents at low cost. Incorporating this signal into a multi-pathway risk model adds an observational dimension that connects the hydrocarbon contamination legacy documented in the UNEP data to the ongoing, incident-driven contamination recorded in the NOSDRA spill archive.

This study addresses the identified gap by constructing a multi-source computational pipeline that ingests heterogeneous contamination data from these three traditions, engineers a spatially consistent 13-feature matrix anchored to georeferenced oil spill incidents and vegetation stress indices, and produces a Composite Risk Score that weights hydrocarbon, heavy metal, and human health exposure pathways according to their empirically derived relative importance. The CRS is interpolated across a 1 km² grid, uncertainty-quantified via Monte Carlo simulation, and validated through spatial leave-one-out cross-validation with Moran's I applied to residuals to test for geographic bias. The resulting dataset and interactive map are publicly released to support community advocacy, regulatory monitoring, and research reproducibility.

The specific contributions of this study are as follows. First, it presents a spatially continuous multi-pathway contamination risk surface for the Niger Delta at 1 km² resolution covering six states with a unified scoring methodology. Second, it demonstrates that a gradient-boosted classifier trained on georeferenced measurement points and a spill-incident-anchored feature set can achieve an AUC of 0.798 for hydrocarbon exceedance prediction in a data-sparse environment, complemented by a heavy metal burden regressor over the same feature set. Third, it introduces a PCA-based pathway weighting procedure that makes the relative contribution of each modelled contamination source an empirical output rather than an expert input, and it treats the human health pathway as a directly computed quantity rather than a modelled one, since the hazard index can be calculated wherever concentrations are measured.

2. Study Area

The study area covers the Niger Delta region of southern Nigeria, bounded by approximately 3.5 to 7.0 degrees North and 4.0 to 10.0 degrees East. The region is characterised by a complex hydrological network of rivers, creeks, tidal channels, and mangrove swamps draining into the Bight of Benin. The climate is tropical humid, with mean annual rainfall ranging from approximately 2,000 mm in the northern delta to over 4,000 mm in the coastal zone, and mean monthly temperatures varying between 25 and 29 degrees Celsius. The mangrove ecosystem of the Niger Delta is among the most extensive in Africa and supports high aquatic and terrestrial biodiversity that is directly exposed to the contamination burden from petroleum industry operations. The combination of high rainfall, poorly drained soils, and dense waterway networks means that contamination introduced at any point in the hydrological system is subject to rapid dispersal and bioaccumulation through the food web.

Six states form the primary geographic scope of the contamination data assembled in this study: Rivers, Bayelsa, Delta, Edo, Akwa Ibom, and Cross River. Rivers State and Bayelsa State account for 39% and 28% of the NOSDRA spill incidents in the dataset respectively, reflecting their concentration of onshore pipeline trunk lines, flow stations, and export terminals. The Ogoni area of Rivers State, comprising the Eleme, Tai, Gokana, and Khana local government areas, represents the highest-density contamination cluster in the dataset. UNEP-documented soil TPH values range from background levels of 2.5 mg/kg to 139,000 mg/kg at a suspended facility site, and groundwater TPH reaches 1,140,000 micrograms per litre. The Ejama-Ebubu site in Eleme LGA, where a crude oil spill occurring during the Nigerian Civil War of 1967 to 1970 has remained unremediated for over five decades, records the single highest soil TPH measurement in the dataset at 49,800 mg/kg, with a hydrocarbon boiling layer documented at 5 cm depth at the time of the UNEP assessment.

The Warri-Escravos corridor in Delta State constitutes the second primary contamination cluster. River Ijana, which receives effluent from the Warri Refining and Petrochemical Company, shows sediment lead concentrations of up to 2.00 mg/g dry weight, and surface water lead values consistently above the WHO drinking water guideline across all sampling points in both seasons (Owamah, 2013). The Trans-Amadi industrial area of Port Harcourt presents a third distinct contamination signature characterised by elevated soil Pb, Zn, Cu, and Cd attributable to industrial activities rather than direct pipeline spill impacts (Okoye et al., 2022). Edo and Cross River States contribute groundwater contamination data from rural communities proximal to pipeline routes, where lead concentrations exceed WHO, SON, and NESREA limits and nickel presents the highest cancer risk among the measured metals, particularly in infants (Dimowo et al., 2025).

The hydrological connectivity of the Niger Delta is a critical factor in the spatial propagation of contamination. The dendritic creek system that characterises the lower delta means that contaminants deposited at a pipeline rupture point in a freshwater environment can reach tidal mangrove zones within hours during high rainfall events, and can enter the marine environment through tidal flushing within days. This dispersal mechanism is particularly relevant for the soluble fraction of petroleum hydrocarbons and for dissolved heavy metal species, which are not retained at the original spill site but travel through the waterway network to affect communities and aquatic habitats downstream. The NOSDRA habitat classification, which records the affected environment for each incident as swamp/freshwater, brackish, mangrove, offshore, or agricultural land, provides partial information about the dispersal pathway of each incident, but does not capture the

downstream extent of contamination transport. Incorporating hydrological transport modelling into future versions of the risk surface, using the Niger Delta digital elevation model and stream network to route contamination from spill points to downstream communities, is identified as a methodological extension that would substantially improve the representation by the model of exposure pathways for communities not directly adjacent to pipeline infrastructure.

3. Data Sources and Compilation

Four primary data sources were integrated into the contamination dataset used in this study. All sources are publicly available, and the compiled structured dataset is archived at github.com/ojochogwu866/nd-public under a CC BY 4.0 licence and submitted to Zenodo for persistent DOI-referenced archiving. The integration process involved manual verification of coordinates, standardisation of measurement units, and resolution of naming discrepancies between data sources.

The integration of these four sources required resolving substantial heterogeneity in coordinate systems, reporting units, and naming conventions. NOSDRA coordinates are provided in decimal degrees and are consistent across the dataset. UNEP Ogoniland coordinates were extracted from site factsheets in degrees-minutes-seconds format and converted to decimal degrees. Peer-reviewed literature coordinates were reported in formats ranging from decimal degrees to cardinal-direction degree strings and were standardised programmatically. Measurement units for heavy metals were standardised to mg/kg for soil and plant tissue and mg/L for water across all nine peer-reviewed sources. These preprocessing decisions are documented in the dataset repository and are reproducible by rerunning the ingestion pipeline against the archived source files.

3.1 Peer-Reviewed Literature (P01-P09)

Nine peer-reviewed studies published between 2009 and 2026 were systematically reviewed and digitised into a structured extraction template comprising nine data sheets covering soil measurements, water and sediment measurements, food crops and fish tissue, health risk indices, spill incidents, reference standards, and geocoded locations. Studies were selected on the basis of three criteria: geographic scope within the Niger Delta, primary data collection with explicit analytical method reporting, and quantitative contamination measurements in at least one of soil, water, food crops, or fish tissue. Studies relying exclusively on secondary literature synthesis or qualitative contamination characterisation were excluded. All nine selected studies used atomic absorption spectrophotometry or ICP-MS for metal quantification and applied internationally recognised reference standards including WHO drinking water guidelines, FAO/WHO food safety limits, USEPA cancer slope factors, and NESREA environmental standards.

The extracted dataset covers 106 georeferenced sample points across Rivers, Delta, Edo, Akwa Ibom, and Cross River States, with measurements of Pb, Cd, As, Hg, Cr, Ni, Cu, and Zn reported in mg/kg for soil and plant tissue matrices and mg/L for water. Health risk indices including hazard quotients per contaminant and aggregate hazard index values were extracted where reported and used to characterise the human health pathway at measured points. Bioconcentration factors and pollution load indices were extracted as supplementary indicators but were not incorporated as model features due to their derivative relationship with the primary concentration measurements, which would introduce target information leakage into the feature engineering step. The fish tissue bioaccumulation data from Bonny River and Finima Creek (Musa et al., 2017) establish that Pb,

Ni, and Cu concentrations in croaker fish gills from Finima exceed FAO maximum permissible limits by substantial margins, providing independent evidence of food-chain contamination transfer that supports the health risk component of the CRS. The geographic distribution of the nine source studies reflects both the contamination geography of the region and the publication geography of Niger Delta environmental research, with Rivers State disproportionately represented relative to its share of NOSDRA spill incidents.

3.2 UNEP Ogoniland Assessment (P10)

The 2011 UNEP Environmental Assessment of Ogoniland provided 120 site-level TPH measurements across five facility categories: SPDC pipeline right-of-way sites (34 sites), suspended facility sites (21 sites), legacy contamination sites (6 sites), NNPC pipeline sites (5 sites), and previously remediated sites (6 sites), with 5 background reference locations. Soil TPH concentrations ranged from 2.5 mg/kg at background reference sites to 139,000 mg/kg at a suspended facility site; groundwater TPH reached 1,140,000 micrograms per litre at a single site near Bodo. Drinking water contamination was confirmed at multiple borehole sites serving local communities, with benzene, a Group 1 human carcinogen, detected at concentrations exceeding WHO limits. Surface water and sediment TPH data were extracted for 27 and 10 locations respectively. The assessment sampled over 4,000 individual specimens across 200 sites using a consortium of international analytical laboratories, giving its measurements a methodological rigour that is unmatched by any other single source in the dataset.

The UNEP data were stored in dedicated Soil_TPH and Water_TPH layers in the GeoPackage, separate from the peer-reviewed heavy metal measurements, given their different measurement paradigm, geographic concentration in Ogoniland, and the distinct contamination narrative they represent. Site coordinates were resolved from individual site factsheets and verified against the map figures in the assessment report. Where coordinates were not explicitly stated, location names were matched against a manually verified geocoded reference table compiled from geographic survey data; remaining unresolved sites were assigned LGA-level centroids within the Ogoni area.

3.3 NOSDRA Oil Spill Monitor

Oil spill incident records were retrieved from the NOSDRA Oil Spill Monitor public API in May 2026 via a purpose-built Python fetcher script. The full dataset comprised 15,630 confirmed spill incidents recorded between 2006 and early 2026. Coordinates are available for all records. Each record includes company name, incident date, estimated spill volume in barrels, cause classification, affected habitat type, Joint Investigation Visit date and participating parties, cleanup date and methods, and quantity recovered where applicable. The volume field represents estimated pre-cleanup spill quantities as assessed during the Joint Investigation Visit; volume values are used in this study as a continuous proximity feature rather than as absolute contamination quantities, and their relative magnitude is treated as more meaningful than their absolute values.

Cause codes were decoded from abbreviated identifiers to plain-text categories: sabotage or third-party interference accounted for 78.2% of all incidents, followed by equipment failure at 8.4%, corrosion at 5.4%, and operational error at 1.7%. Dirty cause code entries were programmatically recategorised based on sub-string matching against known cause types. NAO and SPDC together accounted for 77.3% of all recorded incidents by operator. The total estimated spill volume across the dataset was 714,499 barrels, with a mean of 71.3 barrels per incident and a maximum single-

incident volume of 40,000 barrels. Of the 15,630 total incidents, 9,189 occurred after the Sentinel-2 launch date of June 2015 and were therefore eligible for NDVI analysis.

3.4 Sentinel-2 NDVI

Pre- and post-spill NDVI was extracted for 500 prioritised spill incidents using the Sentinel-2 Surface Reflectance Harmonised collection (COPERNICUS/S2_SR_HARMONIZED) via the Google Earth Engine Python API, authenticated against a registered noncommercial Contributor-tier project. Incidents were prioritised by assigned risk tier, with all critical and high-risk events processed first, followed by remaining incidents sorted by descending estimated spill volume, ensuring that the highest-impact events are represented in the NDVI analysis. A 30-day pre-spill window ending on the incident date and a 30-day post-spill window beginning on the incident date were defined for each event. Cloud cover was filtered to below 20% using the scene-level CLOUDY_PIXEL_PERCENTAGE metadata attribute; this threshold was chosen to balance data availability against data quality in the tropical humid Niger Delta climate, which experiences cloud cover exceeding 70% for much of the year.

NDVI was computed as the normalised difference of Band 8 (NIR, 842 nm) and Band 4 (Red, 665 nm) over a 500-metre circular buffer around each spill centroid at 10-metre native resolution, with per-pixel values aggregated to a spatial mean. Of the 500 queried events, valid pre- and post-spill NDVI pairs were obtained for 421 incidents; the remaining 79 events had insufficient cloud-free coverage within one or both windows. The NDVI delta (post minus pre) was used as the vegetation stress indicator, with negative values indicating canopy decline following the spill event. A vegetation stress feature for each of the 106 model sample points was derived by computing the IDW-weighted mean of negative NDVI deltas across all spill events within 0.25 degrees, with events showing positive or null delta contributing zero. This design propagates the vegetation stress signal spatially from incident locations to nearby measurement sites.

4. Methods

4.1 Data Integration and Spatial Join

All contamination data were loaded from a GeoPackage containing six named layers: soil heavy metals (24 records, P01-P09), soil TPH (78 records, P10), water and sediment heavy metals (45 records, P03-P07), water and sediment TPH (42 records, P10), food crops and fish tissue (22 records, P01, P04, P06), and spill incidents (15,630 records, NOSDRA). A coordinate validation step applied the Niger Delta bounding box (3.5 to 7.0 degrees North, 4.0 to 10.0 degrees East) to filter records; no records fell outside this extent after coordinate resolution. For UNEP TPH sites with null coordinates, resolution was attempted via exact name matching against the geocoded reference sheet, then partial name matching after stripping parenthetical suffixes such as "(pipeline ROW)", then LGA centroid assignment as a final fallback. The HI labels from the Health Risk Indices sheet were resolved to coordinates by the same name-matching hierarchy, with four confirmed HI-exceeded locations successfully resolved and retained as measured human health reference points. All layers were referenced in EPSG:4326.

The choice of GeoPackage as the primary data container reflects the requirements of the multi-layer spatial dataset. GeoPackage is an OGC-standard SQLite-based format that supports multiple named vector layers with independent schemas within a single file, enables spatial indexing, and

is readable by both the GeoPandas Python library and QGIS without format conversion. The use of a single file eliminates the risk of layer-file mismatches that arise with directory-based formats such as Shapefile and provides a single archivable artefact for reproducibility. The GeoPackage was written in EPSG:4326 and validated for completeness by comparing record counts against source extraction templates after each pipeline run.

4.2 Feature Engineering

A 13-column feature matrix was constructed for each of the 106 sample points, comprising the union of the soil heavy metals and soil TPH layers augmented with the four HI-label points. Latitude and longitude were included as positional features. Six spill proximity features were computed via k-d tree radius queries against the full NOSDRA 15,630-incident dataset: spill count and total estimated volume within 0.10, 0.25, and 0.50 degree radii respectively, providing a multi-scale characterisation of incident density around each point. Distance to the nearest recorded spill incident was computed as the Euclidean distance in degree units. Sabotage fraction within 0.25 degrees captured the proportion of incidents attributable to sabotage or third-party interference, as a proxy for chronic pipeline interference intensity rather than episodic operational failure. The k-d tree structure was computed once and reused for all radius queries.

The normalised metal contamination index was computed as the mean, across all metals with measurements at a given sample point, of the ratio of measured concentration to WHO reference limit, with individual ratios capped at three times the limit before averaging. Reference limits applied were 85 mg/kg for Pb, 0.8 mg/kg for Cd, 13 mg/kg for As, 0.5 mg/kg for Hg, 100 mg/kg for Cr, 50 mg/kg for Ni, 36 mg/kg for Cu, and 140 mg/kg for Zn. The resulting index was bounded to [0, 1]. The TPH score was computed as the ratio of measured soil TPH to the EGASPIN soil guideline of 5,000 mg/kg, bounded to [0, 1]; this feature was excluded from the TPH classifier training set to prevent target leakage, as it is a linear transformation of the classification target. By the same principle, the normalised metal index was excluded from the feature set of the metal index regressor, since that index is the regression target, and no metal-derived quantity was used in computing the human health hazard index that could create circularity between the pathways. The NDVI vegetation stress feature was computed as described in Section 3.4. Missing values in any feature were filled with zero, which is the correct expectation value for proximity features at sites with no nearby spill events.

The human health pathway was characterised by computing a hazard index at each sample point as the sum of contaminant hazard quotients for the oral soil ingestion route, following the USEPA risk assessment framework, where each quotient is the ratio of an estimated daily intake to the chronic oral reference dose for that contaminant. Because the hazard index is a deterministic function of measured concentrations, it is reported at measured points only and is not extrapolated across the grid, and it does not enter the composite risk surface. Lead was excluded from the hazard index because it has no consensus oral reference dose. Where a community-level hazard index was reported in the source literature for one of the four health-risk reference locations, that reported value was retained in place of the computed soil-ingestion value; consequently the reported hazard index at those four points reflects the exposure pathways assessed in the original study, which may include ingestion routes beyond soil.

4.3 Model Training

Two XGBoost models were trained against separate targets. The human health pathway was not modelled; its hazard index was computed directly from measured concentrations as described in Section 4.2. The TPH exceedance classifier used a binary target derived directly from UNEP soil TPH measurements relative to the 5,000 mg/kg EGASPIN threshold. The metal index regressor predicted the continuous normalised metal contamination index, with that index excluded from its own feature set to prevent target leakage.

All models used 200 estimators, maximum tree depth of 4, learning rate of 0.05, subsampling rate of 0.8, and column subsampling rate of 0.8. These hyperparameters were selected based on general guidance for XGBoost on small-to-medium tabular datasets and were not tuned through grid search, given the small sample size that would make nested cross-validation for hyperparameter tuning unreliable. Log-loss was the evaluation metric for classifiers and RMSE for the regression model. Cross-validation used 5 folds for both the TPH classifier and the metal regressor. Area under the ROC curve was the primary performance metric for classifiers.

XGBoost was selected over alternative machine learning approaches on the basis of three properties relevant to the dataset characteristics. First, it handles mixed feature types natively without requiring standardisation, which is advantageous given the heterogeneous scale of the 13 features, which range from binary fractions to cumulative spill volumes in the hundreds of thousands of barrels. Second, it provides feature importance scores that support interpretability for regulatory and scientific audiences. Third, gradient-boosted tree methods have demonstrated strong performance in geospatial prediction tasks with small-to-medium sample sizes in peer-reviewed comparisons against random forest, support vector regression, and shallow neural network alternatives. Alternative approaches including Gaussian process regression, which would provide a more principled spatial uncertainty quantification, were considered but judged to require assumptions about spatial correlation structure that are difficult to justify with the available data density. The pipeline architecture is designed to allow substitution of alternative model classes at the training step without changes to the feature engineering or interpolation stages.

4.4 Composite Risk Score

The pathway scores for each of the 106 sample points were assembled into a score matrix of dimensions 106 by 3, comprising the two modelled pathways (TPH and heavy metals) and the computed human health pathway. The human health column was held at zero in this matrix because the hazard index is reported separately and not extrapolated across the grid, so the principal component analysis assigns it zero weight and the composite rests on the two modelled pathways. PCA with a single principal component was applied to this matrix; the absolute values of the first component loadings were normalised to sum to 1 to yield a weight vector. The CRS was then computed as the dot product of the score vector and the weight vector for each point, bounded to [0, 1]. This formulation assigns greater importance to pathways whose scores exhibit greater variance and co-variation with the dominant contamination signal across the dataset. The resulting weights were 0.958 for TPH and 0.042 for heavy metals, with the human health pathway receiving zero weight by construction, reflecting the dominance of extreme TPH values from the UNEP Ogoniland dataset in driving score variance. These weights are fixed for all subsequent grid scoring, ensuring that relative pathway importance is determined by the training data rather than recomputed at each grid cell.

4.5 Spatial Interpolation and Blend Optimisation

The CRS was interpolated from the 106 sample points onto a regular grid of approximately 210,000 cells at 0.01-degree resolution (approximately 1.1 km at the equator) covering the full Niger Delta bounding box. Two signals were blended: an IDW signal computed from the 8 nearest sample points using an inverse-square distance kernel, and a direct model score computed by applying the trained models to a feature matrix constructed for each grid cell using spill proximity and NDVI features matched to the training column order, with metal index and TPH score set to zero at grid cells lacking measurements.

The blend parameter alpha was selected by spatial leave-one-out cross-validation. For each of four candidate values (0.2, 0.3, 0.5, 0.8), each of the 106 sample points was removed in turn and its CRS was predicted from the remaining points using that candidate blend. RMSE across all 106 holdout predictions was computed for each candidate. Alpha of 0.2 was selected, minimising RMSE at 0.0242 against 0.0363, 0.0604, and 0.0967 for the remaining candidates. The selected alpha assigns 20% weight to IDW-anchored interpolation from measured values and 80% to the model-driven prediction from spill features, consistent with the finding that spill proximity features contain more predictive information in spatial holdout than IDW extrapolation across the available measurement density.

4.6 Uncertainty Quantification and Risk Tier Classification

Uncertainty bounds were estimated via Monte Carlo simulation. For each of 100 iterations, independent Gaussian noise with standard deviation 0.1 was added to the full grid feature matrix before recomputing the CRS. The 2.5th and 97.5th percentiles of the 100 CRS values at each grid cell were taken as the lower and upper bounds of the approximate 95% confidence interval. The noise standard deviation of 0.1 was chosen to represent plausible variation in spill proximity feature estimates arising from positional uncertainty in NOSDRA incident coordinates and incomplete incident reporting in the historical record; it does not represent epistemic model uncertainty from training data sparsity. Grid cells were assigned to risk tiers based on CRS: critical (CRS \geq 0.75), high (0.50 to 0.74), medium (0.25 to 0.49), and low (below 0.25). Tier boundaries were defined a priori to reflect approximate quartile structure and are consistent with the contamination exceedance thresholds embedded in the TPH classifier target.

5. Results

5.1 Model Performance

The TPH exceedance classifier achieved a cross-validated AUC of 0.798 with standard deviation 0.189, benefiting from a balanced positive class (49 of 106 sample points with TPH above the EGASPIN threshold). This represents a meaningful improvement over random classification, indicating that the spill proximity and NDVI features carry genuine predictive information about hydrocarbon exceedance independent of direct measurement. The metal index regression model achieved a cross-validated RMSE of 0.024 with standard deviation 0.031, relative to the [0, 1] scale of the normalised target. The human health pathway was computed directly from measured concentrations rather than modelled, so no classifier or regression performance metric applies to it; its hazard index values are reported at the sample points.

Table 1. Model performance summary.

Model	Type	Metric	Value (CV)
TPH exceedance	Classifier	AUC	0.798 (SD 0.189)
Metal Index	Regressor	RMSE	0.024 (SD 0.031)
Human Health (HI)	Computed	—	Not modelled; reported at sample points

The PCA-derived CRS weights allocated 0.958 to the TPH pathway and 0.042 to heavy metals, with the human health pathway excluded from the composite by construction. The dominant weight for TPH reflects the substantially higher variance in TPH pathway scores relative to the metal pathway, a direct consequence of the UNEP dataset containing soil TPH values several orders of magnitude above background and above the EGASPIN threshold. The implications of this weighting for sites outside the Ogoniland data coverage area are discussed in Section 6.

Feature importance analysis from the trained models indicated that the spill-proximity variables, in particular spill count and sabotage fraction within the 25 km radius, were consistently among the highest-ranked predictors for the TPH classifier, while latitude and longitude contributed meaningfully as positional features reflecting the geographic concentration of high-TPH measurements in the Ogoni area. For the metal index regressor, proximity to large-volume spill incidents was the dominant signal, consistent with the interpretation that nearness to high-volume events is the primary correlate of elevated heavy metal burden at measurement sites.

5.2 Spatial Risk Distribution

The interpolated 1 km² risk surface identified 63 critical-risk cells, 551 high-risk cells, 3,496 medium-risk cells, and 205,890 low-risk cells across the full Niger Delta grid. The distribution is heavily right-skewed, consistent with a contamination landscape in which extreme risk is geographically localised to specific industrial and pipeline corridor sites while background risk levels across the broader delta remain relatively low. The 614 critical and high cells collectively represent approximately 614 km² of elevated-risk land surface, which should be interpreted as a model-estimated lower bound given the CRS floor applied in the public dataset export.

The primary high-risk cluster covers the Ogoni area of Rivers State, encompassing Eleme, Tai, Gokana, and Khana local government areas. Within this cluster, critical and high scores are driven principally by the TPH pathway: soil TPH at UNEP-surveyed sites in this area routinely exceeds the 5,000 mg/kg EGASPIN threshold by one to two orders of magnitude. Sabotage fraction within 0.25 degrees at the core Ogoni sites exceeds 0.85, the highest values in the full NOSDRA dataset for any comparably sized geographic area, reflecting the sustained pattern of pipeline interference that has characterised this area since the early 1990s. The combined effect of extreme TPH measurement values and the highest sabotage-associated incident density in the dataset produces the highest CRS values in the Ogoni area, consistent with the UNEP assessment conclusion that the Ogoni area requires the most intensive remediation programme of any sub-region of the delta.

The second primary cluster follows the Warri-Escravos corridor in Delta State. While the composite score across the region is dominated by the hydrocarbon pathway, the Warri corridor

carries a distinct and independently measured heavy metal burden: River Ijana sediment lead of up to 2.00 mg/g dry weight and surface water lead consistently above the WHO drinking water limit across wet and dry seasons (Owamah, 2013) produce elevated metal index values at these sites. Because the composite weighting is driven by the extreme variance of the Ogoniland TPH measurements, this metal burden contributes only modestly to the composite score despite its public health significance, a limitation discussed in Section 6. Total spill count within 0.25 degrees at Warri corridor sites reaches 628 incidents, and spill volume within that radius exceeds 40,000 barrels at the most contaminated measurement points. A secondary cluster of medium-risk cells extends through the Trans-Amadi industrial area of Port Harcourt, spatially coherent with the Okoye et al. (2022) findings. The Buguma Creek area in Asari-Toru LGA shows low to medium scores consistent with the low toxic metal concentrations documented by Oribhabor and Ogbeibu (2009) across two years of monthly monitoring, providing a spatially coherent low-risk reference zone.

The NDVI vegetation stress feature contributed a mean value of 0.031 across sample points, with values above 0.05 concentrated at sites proximal to high-volume post-2015 spill events. Ogoni area sites showed lower NDVI stress values than might be expected from the severity of underlying soil contamination, reflecting the chronic rather than acute nature of Ogoniland contamination relative to the acute event-referenced analysis window. Its inclusion improved 5-fold cross-validated RMSE for the metal regression model by 0.002 relative to the 12-feature model, a modest but consistent gain across all five folds.

The seasonal structure of metal contamination in the Warri corridor is worth noting explicitly. Owamah (2013) reports lead concentrations in River Ijana surface water of 0.032 mg/L in the dry season and 0.028 mg/L in the wet season across the three sampling stations, both consistently above the WHO drinking water guideline of 0.01 mg/L, with cadmium similarly exceeding guidelines in both seasons at all stations. The relative stability of exceedance across seasons suggests that the contamination source is continuous rather than episodic, consistent with ongoing industrial effluent discharge rather than spill-driven pulse contamination. This seasonal pattern is not captured in the current CRS, which is temporally static, but it reinforces the interpretation that the Warri corridor metal risk is structurally embedded in the industrial geography of the area rather than dependent on incident frequency. A temporally resolved version of the model, incorporating seasonal measurement data and incident date-stamped contamination signals, is identified as a development priority for subsequent iterations.

5.3 Validation

Spatial leave-one-out cross-validation produced an MAE of 0.032 and RMSE of 0.121 across the 106 sample points. The negative bias of -0.016 indicates a slight systematic tendency to underpredict CRS values in holdout positions, which is a conservative characteristic for a risk model. The higher RMSE relative to MAE reflects a small number of holdout points with large prediction errors, corresponding to UNEP Ogoniland sites with extreme TPH values that are poorly represented in their IDW neighbourhood when excluded from the training set; these sites have no comparable nearby measurements and their CRS cannot be accurately reconstructed by IDW from surrounding sites with more moderate contamination scores.

Moran's I applied to the 106 SLOOCV residuals returned a value of -0.103, indicating no evidence of positive spatial clustering of prediction errors. A positive Moran's I would suggest that the

model systematically overestimates or underestimates risk in a particular geographic sub-region, which would indicate that a relevant spatial predictor has been omitted. The slightly negative value observed is consistent with the IDW component of the interpolation, which by construction produces a mild negative autocorrelation in residuals when training points are spatially clustered. The magnitude of -0.103 is small and should be interpreted as confirming the absence of problematic spatial structure in the residuals. Tier agreement between stored and computed risk classifications was 100% across all 106 points, confirming internal consistency of the tier assignment logic. The Monte Carlo 95% CI coverage probability against SLOOCV holdout predictions was 0.887.

Table 2. Validation summary.

Metric	Value
SLOOCV MAE	0.032
SLOOCV RMSE	0.121
Bias	-0.016
Moran's I (residuals)	-0.103
MC 95% CI coverage	0.887
Tier agreement	100%
Blend alpha (IDW)	0.20 (empirically selected)

6. Discussion

The empirically derived CRS weighting, which assigns 95.8% of the composite score to the hydrocarbon pathway, emerges directly from the variance structure of the training data rather than from an expert assumption about relative pathway importance. The UNEP Ogoniland dataset contains TPH measurements that in many cases exceed reference thresholds by two to three orders of magnitude; no comparably extreme values exist in the heavy metal dataset assembled from peer-reviewed literature, where exceedances are typically two to ten times the relevant reference limit. This asymmetry drives the first PCA component loading strongly towards the TPH pathway. The practical consequence is that the CRS will assign relatively conservative scores at sites where heavy metal contamination is the primary hazard but TPH data are absent, which applies to a significant portion of the peer-reviewed measurement sites outside Ogoniland.

This should not be interpreted as evidence that heavy metal contamination is of secondary public health importance in the Niger Delta. Groundwater in oil-pollution-prone communities of Edo and Cross River States has been shown to carry carcinogenic and non-carcinogenic health risk from lead, cadmium, and nickel, with the hazard index exceeding the safety threshold in all 113 sampled sources and nickel cancer risk in infants reaching 4.65 times 10^{-3} (Dimowo et al., 2025); food crop contamination at pipeline right-of-way sites in Rivers State has also been reported (Akinkpelumi et al., 2026), as have heavy metal burdens in soil and vegetation elsewhere in the delta (Okoye et al., 2022). The low CRS weight assigned to the metal pathway therefore reflects data scale rather than contamination severity: the UNEP assessment generates extreme TPH scores that compress the relative contribution of heavy metal signals in the PCA decomposition. Future model iterations incorporating wider heavy metal coverage are expected to produce a rebalanced weighting.

The dominance of sabotage-attributed spill density as the primary predictor of elevated CRS has direct and specific implications for contamination risk management in the region. This finding indicates that the spatial distribution of contamination risk is not a stochastic function of pipeline network geometry but is structured by the social and economic conditions that determine the likelihood of third-party pipeline interference in a given area. Communities in historically high-sabotage-rate areas are at elevated risk not only from the cumulative burden of past incidents but from the statistical expectation of future incidents under unchanged conditions. This finding supports the case for community-based environmental monitoring as a proactive risk management strategy in high-risk corridors, rather than reactive contamination assessment following individual incidents. It also suggests that sabotage rate, as a structural predictor of contamination risk, warrants explicit treatment in the environmental and social impact assessments required by international development finance institutions operating in the region.

The 0.887 Monte Carlo CI coverage probability warrants explicit discussion. A well-calibrated 95% CI should contain the true value in approximately 95% of holdout predictions; the achieved coverage of 88.7% indicates that the confidence intervals are somewhat too narrow, by a margin that remains non-trivial for risk communication purposes. The noise-perturbation Monte Carlo approach captures aleatoric uncertainty from feature input variation but does not account for epistemic uncertainty from training data sparsity. With 106 sample points distributed across 70,000 km², a substantial fraction of the 210,000 grid cells are scored by model extrapolation into areas with no proximate measurements, and the true prediction uncertainty in those cells exceeds what the perturbed-feature CI reflects. In areas with high predicted CRS but no proximate contamination measurements, the risk tier should be treated as a model-informed prior requiring ground-truth confirmation rather than as an empirically validated measurement. Conformal prediction methods or Gaussian process regression with explicit spatial correlation structure would provide better-calibrated uncertainty bounds and are identified as methodological priorities for the next model version.

The practical utility of the model for regulatory and commercial applications depends partly on how the risk tiers are communicated and contextualised for non-specialist audiences. The four-tier classification was designed to be interpretable in the context of environmental due diligence screening, where a binary exceed/not-exceed judgment is often required but is poorly supported by spatially sparse measurement data. A site falling within a critical-tier grid cell does not indicate that measured contamination at that specific location has been confirmed to exceed all relevant thresholds; it indicates that the combination of spill incident history, proximity to known contamination sources, and model-predicted contamination scores places that location in the highest risk category relative to the regional baseline. This distinction is important for both the legitimate use of the model as a screening tool to prioritise field investigation, and for avoiding misapplication such as regulatory enforcement based on model output alone without supporting measurement data. The confidence interval fields in the published GeoJSON dataset provide a quantitative expression of prediction uncertainty that should accompany any use of the tier classification in a formal regulatory or commercial context.

The regulatory implications of the model extend beyond the immediate Niger Delta context. The Nigerian Petroleum Industry Act (2021) establishes new host community development obligations and environmental remediation trust fund requirements for petroleum operators, creating a regulatory environment in which spatially explicit contamination risk data has direct commercial and legal relevance. A model-derived risk surface that identifies critical and high-risk grid cells at

1 km² resolution can inform the geographic scope of baseline environmental surveys required for regulatory compliance, support the prioritisation of remediation expenditure under the Hydrocarbon Pollution Remediation Programme (HYPREP), and provide an evidence base for community-level advocacy regarding the adequacy of remediation timelines. The public availability of the dataset and the interactive map at research-map.ojochogwu.dev makes these applications accessible to affected communities and civil society organisations without requiring specialist geospatial software skills.

The data gap between the peer-reviewed measurement coverage and the full geographic extent of petroleum industry operations in the Niger Delta is substantial. The nine peer-reviewed studies assembled in this dataset collectively cover 106 measurement points in a region with hundreds of active oil-producing communities, thousands of kilometres of pipeline, and more than 15,000 recorded spill incidents since 2006. The spatial density of ground-truth measurements is therefore far below what would be required for a purely interpolation-based risk assessment without the model-driven spill proximity features. This gap is not unique to the Niger Delta; it characterises environmental risk assessment in resource-constrained regulatory environments generally, and it is the fundamental motivation for developing a modelling approach that can generate spatially continuous risk information from sparse heterogeneous data. Closing this gap through systematic primary data collection remains the most important research priority, and the model presented here is explicitly designed as a bridge solution until that collection is feasible at scale.

Several additional limitations merit acknowledgment. The peer-reviewed contamination measurements span collection years from 2009 to 2026, and the model therefore represents a spatial average of conditions across a 15-year observation window rather than a current-conditions snapshot. The NDVI analysis is limited to post-2015 spill events and uses a 30-day window well-suited to acute vegetation stress from large-volume events but less sensitive to chronic vegetation degradation from persistent soil contamination at legacy sites. The NOSDRA volume estimates are subject to known dispute between operator and regulatory assessors and should be treated as ordinal rather than cardinal quantities. Original field sampling with standardised methods across the full study area and concurrent collection dates remains the most important single action that would improve model accuracy.

Beyond the Niger Delta, the methodological framework developed in this study is directly applicable to other petroleum and extractive industry regions across sub-Saharan Africa where the same data availability constraints apply. The combination of a public spill incident registry, UNEP or equivalent assessment data, and peer-reviewed contamination literature exists in various forms for petroleum-producing contexts including the Albertine Graben in Uganda and the offshore-onshore transition zones of Ghana. In each case, the pipeline presented here can be adapted with region-specific reference standards and locally available contamination measurement literature, producing a comparable CRS surface that enables cross-regional comparison of contamination risk intensity.

7. Conclusion

This study presents a multi-pathway contamination risk model for the Niger Delta that integrates hydrocarbon and heavy metal contamination measurements, health risk assessment data, oil spill incident records, and satellite-derived vegetation stress indices within a unified computational framework. The model produces a spatially continuous Composite Risk Score at 1 km² resolution

across six states, with PCA-derived pathway weights, an SLOOCV-optimised spatial interpolation strategy, and Monte Carlo confidence intervals. A cross-validated AUC of 0.798 for the TPH classifier and a metal index RMSE of 0.024 indicate that spill proximity and vegetation stress features carry genuine predictive information about contamination exceedance across a 70,000 km² study area despite the sparsity of the ground-truth measurement dataset, while the human health pathway was characterised directly from measured hazard index values rather than by model prediction. Critical and high-risk cells are concentrated in the Ogoni area of Rivers State and the Warri-Escravos corridor of Delta State. Sabotage-attributed spill incident density emerges as the dominant structural predictor of elevated composite risk, consistent with the established pattern of pipeline interference in the region and with the contamination geography documented in the UNEP assessment and peer-reviewed literature.

The compiled contamination dataset, the scoring pipeline, and the interactive risk map are released publicly under open licences to support community advocacy, regulatory monitoring, and research reproducibility. The framework is designed to be extensible: original field measurements, additional state coverage, and temporal updating of the spill incident dataset can all be incorporated within the existing architecture without structural modification. The most consequential near-term improvement would be a targeted original field sampling campaign using the existing risk surface to prioritise high-uncertainty areas for measurement, which would both validate the current model output and provide training data sufficient to substantially improve classifier performance, particularly for the heavy metal pathway. The extension of this continental environmental intelligence framework to other petroleum and mining regions across sub-Saharan Africa is identified as a long-term objective of the research programme.

The interactive risk map hosted at research-map.ojochogwu.dev is designed to make the model outputs accessible to non-specialist audiences, including affected community members, local government officials, and journalists, as well as to environmental practitioners and researchers. The map renders the four GeoJSON outputs from the scoring pipeline on a satellite base layer, with colour-coded risk tiers, hover tooltips displaying pathway subscores and CRS values, and a model information panel showing cross-validated performance metrics. The decision to make model performance metrics directly accessible in the user interface rather than restricting them to the academic paper reflects a commitment to transparency about the limitations of model-derived risk estimates. Users who engage with the map as a tool for community advocacy or regulatory engagement are thereby informed about the uncertainty of the risk surface they are citing, and can make informed decisions about when to treat model output as sufficient evidence and when to request ground-truth measurement data to support a claim.

Beyond the Niger Delta, the methodological framework developed in this study is directly applicable to other petroleum and extractive industry regions across sub-Saharan Africa where the same data availability constraints apply. In Uganda, the Albertine Graben development corridor has an active National Environment Management Authority spill registry, UNEP-affiliated baseline environmental assessments for the Tilenga and Kingfisher project areas, and a growing body of peer-reviewed contamination literature from Makerere University and international collaborators, providing the three data pillars required to run an equivalent pipeline. In Ghana, the Environmental Protection Agency maintains an offshore incident registry for the Jubilee and TEN field areas, and soil and water contamination measurements from the onshore processing zone at Atuabo are available in the peer-reviewed literature. In the Democratic Republic of Congo, the artisanal and small-scale mining regions of Katanga Province have been the subject of multiple

heavy metal contamination studies documenting cobalt, copper, and lead exceedances in soil, water, and agricultural produce, with GPS-referenced sampling coordinates that would support direct ingestion into the feature engineering pipeline. In each case, the adaptation required is primarily one of reference standard substitution, replacing EGASPIN with the relevant national environmental standard, and spill incident data source substitution, with the core feature engineering, model training, and interpolation architecture remaining unchanged. The extension of this framework to a continental African contamination risk intelligence layer, enabling cross-regional comparison of contamination burden from petroleum and mining operations, is identified as the long-term objective of the research programme initiated by this study.

Data Availability

The compiled contamination dataset and processed GeoJSON outputs are available at Github: <https://github.com/Ojochogwu866/nd-public> under CC BY 4.0. A Zenodo DOI: <https://doi.org/10.5281/zenodo.20306425>. The interactive risk map is available at <https://research-map.ojochogwu.dev>.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

D.O.D.: Conceptualization, methodology, software, data curation, formal analysis, writing — original draft preparation, writing — review and editing, visualization. The author has read and agreed to the published version of the manuscript.

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