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Development of a Novel Oil Spill Severity Index (OSSI) for the Niger Delta

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Abstract

Oil spills remain a primary issue of environmental and socio-spatial consequence in the Niger Delta. Typical oil spill assessment methods are based on specific and singular measures, such as volume of spill and the dimension of the contaminated area, with due consideration not given to the spatial proximity of spill to water resources and communities. This work developed a novel Oil Spill Severity Index (OSSI), a composite measure designed to rank spill sites according to urgency for remediation. The OSSI integrates four indicators: spatial extent of contamination, volume of oil released, proximity to residential communities, and closeness to essential water sources. GIS were used to derive the two proximity variables from the spatial location of incidents; while the indicators were normalized and weight aggregated to develop a single dimensionless index of spill severity (0-100). Four weighting scenarios were used in analyses to compare results obtained when Equal Weighting, Social Priority and Ecological Priority schemes are applied. Model validity was evaluated through Monte Carlo simulation, and bootstrap resampling and differences between severity class were assessed using ANOVA while variations in classifications under alternate weightings were assessed using Chi-square. Sensitivity analysis results show that distance to communities is the most significant factor influencing sensitivity coefficient (SC), with a SC value of 0.41, followed by distance to watercourses (SC=0.29), Spill volume (SC=0.18), and Contaminated Area (SC=0.12). Additionally, the weighting analysis found that the social priority management perspective, compared to the equal and ecological priorities, increases number of high and very high categories cases. This study presents a pioneering effort to combine spill magnitude, settlement proximity, and ecological exposure within a unified severity model. This study enhances environmental risk classification, spill prioritization, and policy-based decision-making by identifying critical spill hotspots that conventional approaches may fail to detect.

Keywords: Oil Spill Severity Index (OSSI); Niger Delta; Oil Spill; Geographic Information System (GIS); Multi-Criteria Decision Analysis; Remediation prioritization.

Introduction

Oil pollution is a persistent environmental issue in the Niger Delta; with impacts on ecological systems, livelihood, food security and human wellbeing. Pollution from petroleum can affect the soil resources of agricultural land and the water resources in streams and rivers thereby imposing further pressure upon livelihood activities of inhabitants that directly rely on land and water resources as their income and food. Studies documenting on petroleum impacts to aquatic ecosystem resources within the Niger Delta also bear the evidence on the significance of continual petroleum contamination on environment (Igbani et al., 2024). Thus, severity of a spill event is not only concerned with a size (or amount) but also its location with relation to its possible victims or environmental receptor.

Substantial spatial variation exists in the extent of the problem in the Niger Delta, from evidence on geospatial approaches, with studies by Akinwumiju et al. (2020) identifying patterns on spill pollution based on geographical coordinates of petroleum infrastructure and environmental variables. This is supported by newer investigations focusing on determining the risk assessment using source characteristics, environmental pathways and receptor characteristics, where spill characteristics and environmental factors such as proximity to streams, oil infrastructure and population-based factors were considered alongside to present their influence on groundwater contamination in the Niger Delta (Oyebamiji et al., 2025). This implies that spill characteristics is incomplete, when considered on isolation as a size measure in explaining different relative severity of oil spill events.

Therefore, a spatially differentiated analysis is crucial where there exists proximity or distance of oil spill incident with regards to human settlement and river systems. In these occurrences, moderate spills near densely populated areas or other potentially affected receptors will attract high consideration compared to large spill in very remote locations. It implies that only a measure considering not only physical dimensions of the spill but also its close relation to certain human and environmental components would suffice to determine incident criticality in comparison between others. This has necessitated a review in methods where composite analyses considering independent characteristics simultaneously will differentiate spill severity.

Several studies have indicated the usefulness of integrating parameters in GIS for the purpose of establishing a differentiated sensitivity analysis, such as, a study that develop a terrestrial environmental sensitivity index of the coastal Niger Delta (Wekpe et al., 2024a) based on integrated GIS and multi criteria analysis (MCA), as well as a multi-criteria GIS-based approach to assessing risk of oil spill (Wang et al., 2023).

This research, based on this premise, develops an Oil Spill Severity Index (OSSI) for the Niger Delta, which integrates Environmental Magnitude (EM) and Socio-Temporal (ST) characteristics, where Environmental Magnitude refers to the physical properties of a spill incident (i.e. Volume and affected area) and Socio-Temporal takes into account spatial interrelationships between spill location relative to human settlements and water bodies and temporal aspects of reported spills. GIS is utilized to calculate spatial interrelationships while MCDA is employed to normalize, weight, and sum up selected parameters to constitute the OSSI score.

The study uses oil spill incidents recorded during 2019-2023 which encompasses the same data range as used by Siloko et al. (2025). Selected parameters have their scores estimated through a weighted MCA procedure on spatial analysis to derive an OSSI value for each spill event. Following this, the derived OSSI scores are analyzed to determine areas or periods having higher or lower spill severity among evaluated spills. Because composite indices can be influenced by the choice of criteria weighting structure, this study includes an evaluation of its robustness using a Monte Carlo approach coupled with bootstrap sampling. The outcome will be a description on which oil spills have higher severity regardless of weighting conditions being used.

Overall, the study provides a spatially aware event-specific risk appraisal framework for comparative evaluation and relative prioritization of oil spill incidents in the Niger Delta for the purposes of further monitoring and investigation purposes. It does not aim at measuring directly actual environmental impact, human health consequences or loss associated with the incident but rather provides a transparent and reproducible framework on their likelihood and potential critical areas and periods relative to their spatial positioning.

1.1 Theoretical and Conceptual Framework: Development of OSSI

1.1.1 Environmental Risk and Vulnerability Theory

Conceptual framework of OSSI is anchored in environment risk and vulnerability paradigm which perceives risk as resultant of the interaction between the occurrence of hazard and the nature of the phenomenon in relation to its receptor based on terms that take account of the potential consequences associated to the hazard exposure which cannot solely defined from hazard characteristics (Intergovernmental Panel on Climate Change, 2022) Within this understanding, parameters representing extent and size of the oil spill are essential but not absolute; factors such as spatial occurrence of an incident relative to settlements, water courses, sensitive receptors etc. is equally critical as they would determine interaction of event with human and environmental receptors. Evidence on the analysis in Niger Delta showed clear evidence on spatial characteristics. Akinwumiju et al. (2020) concluded that oil spill pollution is strongly and clearly associated with spatial distribution; as well as, Oyebamiji et al. (2025) illustrated how spill characteristics may consider together with spatial extent of receptor along a spill-pathway.

Therefore, spill magnitude should be interpreted as having a relative significance through the consideration of location proximity with regards to potential receptors. It is important, however, to define such proximities not as factual indications of impact but as proxy of interaction; not indicating the consequence, rather explaining that a factor is present around a spill event. By segmenting spill physical characteristics from potential receptor interactions, while spill volume and surface area are part of environmental magnitude characteristic, space between spill event and settlements/water body constitute Socio-temporal characteristic by placing potential relationship to receptors at the center; event at greater distance from the potentially affected receptor is considered less severe. This means for a given spill size an index value can significantly fluctuate due to the event location as it interacts directly with human beings and resources. Therefore, proximity is interpreted as a proximity relation for potential human habitation and surrounding resource components rather than direct relation to human health or livelihood and environment degradation.

1.1.2 Socio-ecological System Theory

The conceptual framework of OSSI is also based on the socio-ecologic system paradigm (SES), considering its relevancy with the social context of the Niger Delta, whereby inhabitants utilize water and land resources for a wide variety of needs such as water use for drinking and other domestic purposes, fishing and subsistence livelihood practices and others through direct interfacing with their surrounding ecosystem. Thus, the risk implications of petroleum pollution impacts would also expand and affect its interconnected social constituents. Oil impact on aquatic system with regards of resources are crucial in the Niger Delta (Igbani et al., 2024) as part of broader system interactions (Saja et al., 2021).

Interactions among both the social and natural system define this paradigm; human system may use a water resource in Niger Delta for survival; water resources might support life for various living things within the ecosystem and provide means for interaction.

Spatial positioning aspect in the SES perspective comes into play in linking directly an oil spill event, which is a direct nature event, with human settlements and river systems as a medium for interactions. Proximity could not be interpreted solely in determining actual impact and degree of vulnerability/health problems, since factors such as population number and density; state of the aquatic resource itself, and extent/degree of persistence may alter potential impacts. Therefore, in the present study an OSSI that accounts for interaction (both direct and indirect) with social (human settlements) and ecological (river system) part of the surrounding environment will provide better means in understanding a spill event.

1.1.3 Multi-Criteria Decision Analysis (MCDA) Method

The operational logic of the OSSI builds upon multi-criteria decision analysis (MCDA). MCDA is the technique employed in cases where one must make an assessment that comprises a range of different and disparate indicators (Wang et al., 2023). An oil-spill assessment requires measures such as volume, spatial extent, and distance to people or water bodies to be combined even though they are measured in different units and scales and carry different implications regarding their meaning. In developing the OSSI thus, the indicators were first standardized by means of scoring and then weighted to reflect their relative importance within the context of an environmental disaster assessment.

This mirrors established practice in spatial based environmental sensitivity, and oil-spill risk assessments that use MCDA in the development of indices by integrating multiple spatial parameters to form composite analyses (Wang et al., 2023; Wekpe et al., 2024b). The weighing component is particularly critical, since a shift in importance of one or more criteria can lead to variations in composite scores, and rank ordering of incidents. Monte Carlo and bootstrap analyses were therefore used to compare results obtained under different combinations of weighting schemes for each criterion (sensitivity analysis). In doing this, we tested whether the observed ranking for each event against standard criteria was a true reflection of environmental reality or a result of particular weighting schemes used.

In effect, the MCDA framework becomes a methodological pathway linking the underlying theories of the OSSI to its physical or real-world expression-translating such concepts into measures of environmental concern while being transparent on any assumed weights and parameters for generating composite indexes.

2. Literature Review

Recent scholarship dealing with oil pollution has increasingly focused less on simple reporting of damage and more on aspects of environmental exposure, environmental sensitivity, remote-sensing verification of spill impacts, vulnerability, and, where appropriate, a multiplicity of criteria used for oil-spill assessment. The implication is that the significance of an oil-spill incident is now more than just its physical characteristics-that environmental and receptor considerations become critical components when determining environmental impact. All these constitute the analytical framework for the creation of an Oil Spill Severity Index (OSSI).

2.1 Environmental impacts and a multi-criteria oil-spill assessment framework

Petroleum contamination has impacted both aquatic and terrestrial ecosystems within the Niger Delta. Effects reported by Igbani et al. (2024) were so severe to the resources of an entire watershed; Obida et al. (2021) report massive vegetation dieback associated with a spill that affected a vast portion and occupied a large amount of space and habitation within the Ogoniland of the Niger Delta while a study by Akinwumiju et al. (2020) illustrates, unequivocally, that petroleum spills in the Niger Delta do not occur and affect the local and global environment uniformally but differ in location and magnitude. While this type of response to spilled hydrocarbons is consistent, to some extent, among different parts of the world (Muhammad et al., 2024) its manifestations are different: microbial populations and metallic contaminants responded in tandem during petroleum spills (Muhammad et al., 2024); different vegetation response types exist that relate the nature of spilled product to vegetation type, environmental state, location of spill and duration of occurrence (Kuta et al., 2025). While the foregoing implies volume is not everything, it does indicate that any interpretation of spill severity in the Niger Delta should take spill size and extent of impacted environmental elements into consideration along with the receptor it affects.

2.2 Volume, affected area and physical aspects of oil spill impact

The total quantity of spilled petroleum, when quantified, can serve as a single reference parameter in establishing physical aspects of spill impact. However, volume alone does not reveal the spatial extent that the spill might have or the ecological receptors the spill may affect. It is for this reason that 'affected area,' which estimates the spatial dimensions of a spill, is another crucial indicator. Examples of how large spills can directly cause massive damage to ecosystems are found with observations of significant impacts to vegetation, Obida et al. (2021). Geographic variations of oil-spill occurrences, impacted environs, and environmental states associated therewith in the Niger Delta have also been demonstrated. Akinwumiju et al. (2020) found significant geographical variability of environmental states in the areas of recorded spills, and satellite data has been used extensively by Obida et al. (2021) to illustrate extent of terrestrial contamination, while Adebangbe et al. (2025) integrates satellite sourced information into oil spill analysis that was correlated with

recorded volume to estimate contaminated areas. Combining data on spill volume and spatial extents therefore helps estimate the true physical extent of an oil spill impact. The OSSI measures EM with this principle: Volume (V) and Area (A) have been combined to provide a proxy of EM, thereby taking into consideration both the magnitude of release and its extent across a region.

2.3 Distance to ecological and social receptors, and potential receptors

Awareness that it is important for potential receptors to be close to spills, even in scenarios that share one major physical variable(s) with another spill but at a greater distance, grew with increased interest in spatial impacts and the interactions between physical spills and their geographical contexts. Studies show that people live within spilled sites, as seen in Obida et al. (2021); even more work has incorporated the 'source-pathway-receptor' model to show that, besides being exposed, receptor sensitivity varies: receptor population at source/receptor sites, proximity of water bodies to spills, distance of water courses and spill source to people and infrastructure-linked entities of water resources (Oyebamiji et al., 2025). Likewise Umar et al. (2024) estimated susceptibility zones in groundwater sources using an integration of DRASTIC and weight of evidence. It shows that if the physical parameters are the same between two events, the probability that an incident may be more or less disastrous than another due to physical characteristics does not lie purely with the physical parameters but also with the geographic context and placement of the disaster in space. Thus, the two critical parameters chosen for distance to receptors are the distances from spill sources to human communities and distance from spill sources to nearby water bodies. A decreasing distance signifies greater probability of contamination for both receptor types, and therefore their relative values need to be inversely standardized. While this distance component does signify a condition whereby receptors are exposed they are by nature estimations; any actual ecological injury, health effect or economic damage depends on whether or not the mentioned receptors (ecosystem or population) have indeed been contaminated with petroleum. Site-specific investigation would thus require additional information or evidence.

2.4 GIS, MCDA as tool in Environmental Sensitivity Assessment

Combining three techniques-GIS, remote sensing and MCDA-together forms the standard methodology adopted within environmental sensitivity assessments of spills, land contamination or ecosystem damage (Wekpe et al., 2024a; Oyebamiji et al., 2025). These three methods allow disparate data items and values at varying units and measurement scales to be converted into readily comparable index components, which are then used and weighed appropriately in forming composite measures and making rankings. This approach can be applied to spills and is used in assessing areas where high ecological/social values are potentially present: for example, it helped determine that coastal areas within the Niger Delta show vastly different environmental sensitivities.

Similarly, at local and regional levels groundwater contamination has also been assessed by integrating individual factor weights to produce a risk surface using source, pathways, receptors, and additional related GIS layer(s) and factors(s) (Oyebamiji et al., 2025; Wekpe et al., 2024b).

Most work integrating GIS/remote-sensing/MCDA approaches tends to focus on environmental sensitivities or risk posed by an oil-spill threat or an existing situation. Applying such combined approach for indicating actual event severities instead makes it very important.

2.5 Timescale of oil spills

With regards to the variable of time, based on the above, it is also possible that differing magnitudes of impact can stem from different individual spills. Based on an inventory of oil spills, Siloko et al. (2025) identified and concluded that incidents, as well as their volumes, differed in their occurrence in time. Furthermore, differing environmental responses could be expected dependent on when a spill had occurred (Kuta et al., 2025).

None of the above means that a particular event would automatically be greater as a result of a high frequency of it happening or as a result of only taking up to date information regarding a spill's extent, occurrence etc. Hence time based data was largely excluded from a quantitive measure of the event's impact, other than in specific, cautiously measured and logically explainable, linear relationships against the specified indices where stated criteria.

2.6 Methodological Gap and Rationale for OSSI

Plenty of research has focused on oil contamination, spatial patterns of spills, environmental sensitivity of receptors to contamination, their exposure, their vulnerability and in particular temporal dynamics in the Niger Delta (Akinwumiju et al., 2020; Obida et al., 2021; Oyebamiji et al., 2025; Umar et al., 2024; Wekpe et al., 2024a; Kuta et al., 2025; Siloko et al., 2025; Adebangbe et al., 2025). Many of these, however deal with specific dimensions of an oil-spill, and provide no composite measure which could be used for event comparison.

Thus the main methodological gap that this paper seeks to bridge is a need to develop an event-based composite measure, to allow the comparative ranking of oil spills by level of severity, with resultant management priorities. This index would bring Environmental Magnitude (EM) and Socio-Temporal (ST) data together (see definition). EM could include variables such as spills volume (V) and affected area (A), while ST would encompass not only the spatial relationship between spills and settlements or water bodies but, where definition allows, temporal information concerning them also.

With standardisation and weighted multi-criteria decision making, the chosen indicators are put into a common scale upon which the events may be measured against each other and then, using Monte Carlo simulation and bootstraps, the robustness of results were assessed against the uncertainty attributed to weighting structure. The final index should thus be a relative index rather than a measure of environmental impact. Higher scores thus indicates comparably greater physical magnitude and receptor exposure to the spill itself but are not themselves an indication of an ecological, health or economic impact, among many others.

3. Methodology (Background + Novelty)

This research presents a novel integrated geospatial and statistical modeling methodology for developing an Oil Spill Severity Index (OSSI) in the Niger Delta. Traditional oil spill risk assessment tools typically utilize a single measure, such as spill volume or impacted surface area, without accounting for important spatial characteristics, socio-environmental vulnerabilities, and the interrelationships among multiple risk factors, thus limiting their effectiveness for targeted intervention and policy development. In contrast to previous methodologies that address specific elements of risk through a single parameter or measure, OSSI integrates both hazard characteristics (environmental spill magnitude) and socio-spatial exposures. While similar multi-indicator tools have been developed elsewhere and applied in regions with extensive oil operations, to the best of our knowledge they are yet to be applied in a complex socio-ecological setting such as the Niger Delta, where intense industrial presence intersects with highly sensitive ecosystems and densely populated human settlements.

The developed OSSI therefore represents the first integration of a multidimensional oil spill severity index in the Niger Delta, a crucial step towards advancing risk management in a region heavily dependent on natural resources. This methodological framework allows for the combination of hazard, exposure and vulnerability parameters in assessing impacts from both environmental and human perspective to build a coherent framework for decision making under multiple risk scenarios. Thus, this framework is expected to improve the ability to recognize difference in spill impacts with reference to environmental and socio-spatial settings.

3.1 Data Sources and Data Preparation

The diverse data source includes data from official reports of all incidents associated with petroleum occurred on various locations between 2019-2023. This includes: the number of incidence occurrence over a given period; estimated discharge volumes and the extent of effected area; the causing facts of this oil spills such as device defect, machine failure and sabotage (Siloko, Ukhurebor & Otsupius, 2025). In terms of the environmental factors and the exposure risk of population, spatial data was incorporated in the study for GIS techniques supported by high resolution satellite imaging. This was applied in analysis of spatial relationships which include geographical position of spill occurrence the residential area as well as major water bodies within it. GIS was also used to obtain settlements information from census data which includes raster images derived from base maps on census data and spatial data on river and creeks which were digitized into layers for ease of use. The entire collected and collated layers were transformed into a unified projection system (coordinate reference system) and processed for subsequent data analysis.

3.2 Conceptualization of OSSI (oil Spill Severity Index) and Indicator Selection

OSSI application was based on the concepts derived from the theory of environmental risk and vulnerability, social–ecological system (SES) and a method developed by combining the indicators on the basis of MCDA theory which defines the environmental risk as the combine concept of magnitude, intensity and vulnerability. Based on this conception, four basic indicators were selected and formulated: spill volume (reflecting magnitude), affected area (representing scope), distances to settlement and distance to water bodies (measuring human and environmental

exposures respectively). This method combines the direct impact with socio-spatial attributes commonly overlooked in conventional models.

3.3 Determination of indicator weightages on stakeholders' level

In order to make the index more context driven, weightages are generated on stakeholders' level. While environmental scientists share technical viewpoint over issue of ecological risks (Akpan, 2022, 2023) other professionals/policy makers, regulators provide perspective towards what should be given more emphasis. Local stakeholders focus on the ground effect of pollution and threat on their livelihoods and properties around water bodies and residential areas. Based on the above and the MCDA process, three sets of weightings schemes: ecological concern, social concern and balanced are created in which relative weights assigned to indicators reflect a particular priorities: spill volume and effected area more important; proximity to water body and settlement greater emphasis; and in a balanced concern the equal weighted applied to all variables.

3.4 Implementation of Geospatial Information Systems Tools for Indicator Derivation

Geospatial Information Systems techniques, namely QGIS software and ArcGIS pro software were adopted and used to derived indices and indicators, whereby buffering was practiced for the distance based indicators. Similarly, overlay, spatial joins and proximity tools were used to spatially relate and integrate all selected indicator related dataset. Buffer tools were utilized for calculating the proximity distance of any oil spill site to nearby communities and important water bodies such as, rivers, lakes and ponds. And by utilizing such tool, an appropriate level for human exposure and also natural exposure was successfully created into standardized spatial indicators.

3.5 Developing Oil Spill Severity Index (OSSI) Model

The OSSI model used here to assess the relative severity level of oil spills occurrences by the integration of a composite of derived indicators with assigned weights, wherein four main categories of severity-index indicators have been designed: distances from human communities(i), distances from major water bodies(ii), spill volumes (iii) and contaminated area (iv). The choice of these components reflects their relative significance with regard to the potential environmental effects and human exposure associated with the spills. The oil spill severity Index (OSSI) model developed is based on the Eq. 1:

$$OSSI = Wd1[d1] + Wd2[d2] + Wv[V] + Wa[A] \quad [1]$$

Where, W[d1], W[d2], W[V], W[A] are weight coefficients for distances from human communities, waters bodies, spill volumes and affected area respectively, while the corresponding I[d1], I[d2], I[V], I[A] are the normalized (standardized) form of these indicators. The normalization of individual features into (Ii) ensures the comparability of these variables so that their weighted values will be additive and comparable in the computed value of the OSSI index.

3.5.1 Conceptual interpretation of OSSI Model

The OSSI, an MCDA approach has adopted a weighted composite based methods, thereby the level of danger posed by each spill event to human, economic or environmental is based on the influence of combinations of various site specific and the environment specific attributes and characteristics. Thus it takes into account multiple attributes; distances from human settlements is used as proxy for the level of human exposure to risks; distances from major bodies, such as rivers and lakes is utilized as a proxy for potential ecological damages; spill volume determines the magnitudes of the release; and it has to take into account of extent of landmass being contaminated. Instead of only depending on a single measurement indicator as conventional risk index usually do, the OSSI combines all the above parameters into single index thus allows for better representation of risks. The original measurements were therefore transformed into a normalized index [Ii] which represents various measures of risk level based on the level of exposed distance.

For each distance I[di] variable i=d1.

d2; weight coefficient i multiplied the normalization (measure in i =0…. 10). This gives an expression that makes meaningful sum of heterogeneous measures. The individual normalized variables I[i] were then weighed in order to represent the relative degree of importance that stakeholders assign to each dimension for the assessment of the Oil Spill risk.

Therefore, to reach the OSSI index value the individual normalized values of all four attributes have been disaggregate as follows in Equation 2.

The summation (of the) w{i} value, that is:

$$\text{sum}\{i\}^{n}w\{i\} = 1 \qquad [2]$$

Where i range from 1 to 4 and the i-th weight may be considered as the "importance factor". The w{i} represents contribution degree of i, attributes of the measured. The sum of the co-efficient weight for the indicator was fixed at unity so as to maintain proportionality among various factor being discussed in here in regard to contributing part or role to make up overall assessment value(OSSI value).

3.5.2 Role of Weighting Co-efficient

The weight co-efficient used in the index measures the degree of contribution of each individual variable to OSSI value. These w{i} values reflect that not all the variables presented in the model contribute equally to severity-index value. Depending on a planner's primary goal (e.g. environmental conservation, human welfare and etc.), a different focus can be placed on attributes.

It can be that environmental scientists pay most attention to environmental factors (as example; distance to water body and affected area), other professionals may emphasize proximity of oil to house (d1) and size of spillage (volume). The weight values have been constrained in sum equals to one, because this represents a logical and acceptable form of assigning priorities and weight to various criteria for decision making under uncertainty for example (Yusuff & Ukhurebor, 2020, 2021).

3.5.3 Analytical significancy of OSSI

The OSSI model offers a single index tool that could facilitate comparison, grouping, prioritization and selection of appropriate strategies against the oil spill incidence through comprehensive and integrated process by considering diverse aspects and variables of such incidence that affect and impact the study area. The major importance of the model in general is its ability to integrate various variables measuring different units of scales with different units of measures and other measurement parameters.

Normalization ensures that the chosen indicators are scaled such that their values can readily be compared and combined through a summation to calculate a relative severity score. Under this formulation the human threat, ecological threat, size of spill and extent of contamination can be assessed simultaneously. Further by using the weighting scheme relative impacts between these four indicators can be weighed according to policy or human or ecological need, or simply to achieve a sensible and robust output.

In this case, use of the OSSI allows us to compare single spills of the same type of pollution to other oil spills; in terms of their relative impacts we can therefore more clearly identify where the combined ecological threats and potential human threats demand increased monitoring, protection or rehabilitation. Thus, OSSI can assist in prioritization of areas with high environmental and human damage potential relative to oil spill incident response.

The result produced by OSSI FSI can vary from 0-100. These were sub-divided into four levels: 0-25 Low; 26-50 Medium; 51-75 High; 76-100 Very High. These can serve as a tool for prioritizing oil spill remediation efforts for various location and conditions (Fig. 1).

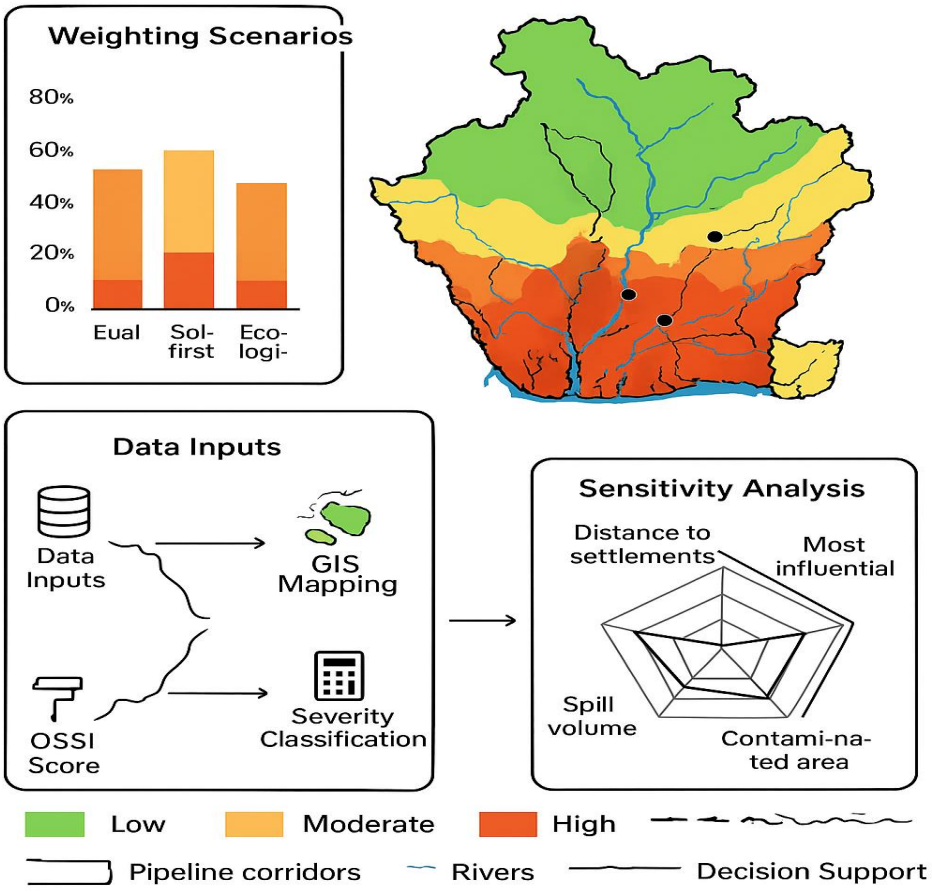


Fig. 1 Integrated Oil Spill Severity Index (OSSI) in Niger delta

3.6 Normalization and Severity Classification

To ensure uniformity, all indicators were normalized to a common scale. The total weight was standardized to 20, and the Final Severity Index (FSI) was computed as:

$$FSI=\sum(W_i \cdot I_i)2FSI \quad [3]$$

The resulting FSI values (ranging from 0 to 100) were classified into four categories:

Low: 0–25

Medium: 26–50

High: 51–75

Very High: 76–100

These classifications provide a practical basis for prioritizing intervention and remediation efforts by providing actionable tiers to prioritize spill response and remediation as shown in Fig. 2.

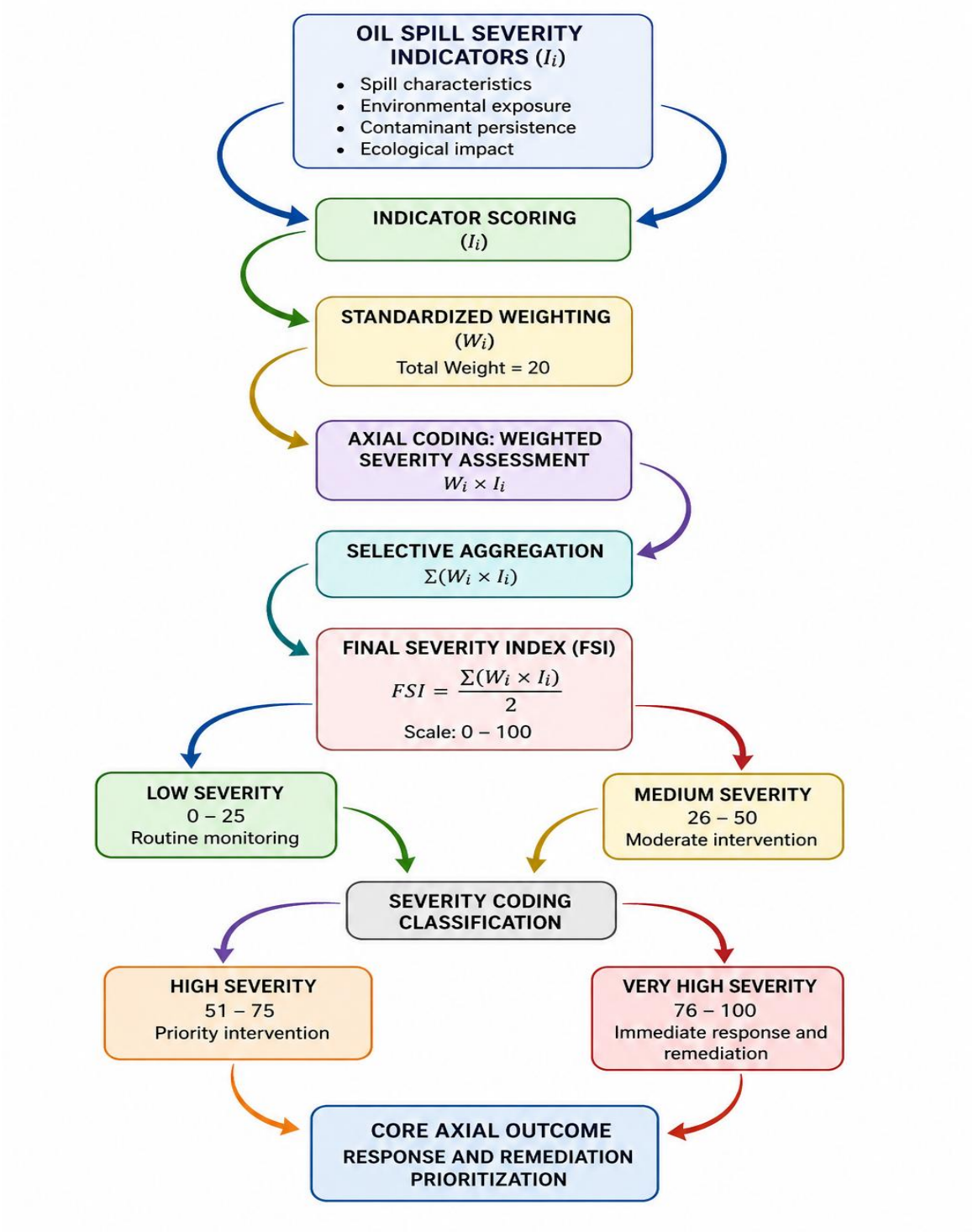


Fig. 2. Integrated Oil Spill Severity Index (OSSI) in Niger delta

3.7 Statistical Analysis and Model Validation

To enhance reliability of the index, statistical validation procedures were performed using Python and R. We used a Monte Carlo simulation approach (1,000 iterations), run in Python (libraries NumPy and SciPy), to analyze OSSI uncertainty. We also employed a bootstrap re-sampling procedure in R to gauge model stability and used inferential statistical tests (such as ANOVA and Chi-square test) run in R to study the relationships among severity levels and spatial variables. Such statistical validation helps build confidence regarding model robustness and reproducibility.

3.8 Software and Analytical Environment

A number of software packages were integrated in the analytical process for different tasks, including spatial analysis (ArcGIS Pro and QGIS for calculation of proximity, overlays, etc.); computational index (Python (NumPy, Pandas, SciPy)); statistics and verification (R); visualization and plotting (Microsoft Excel and OriginPro).

3.9 Methodological Justification (Novelty and Context)

The OSSI methodology was constructed in a response to the weaknesses of typical methods for classifying the impact of oil spills – typically considering individual indicators only and missing out effects of spatial proximity and sociopolitical consequences. OSSI, a spatially referenced risk tool combining GIS, MCDA and statistical analysis, allows for assessing an oil spill context-independently. Our application of the OSSI framework in Niger Delta is unique; the risk is estimated through an integrated (ecological, human, infrastructure) concept and for the first time in this specific geographical context through local applicability. The index and sub-indicators were tailored on the socio-economic and ecological characteristics specific to the Niger delta. Global nature of impact was also considered based on key, interrelated, spill parameters, ranging from their size, surface area to distance of settlements. Another novel feature of OSSI is the inclusion of local expertise: criteria and sub-criteria are based on consultation with local communities, officials, environmental experts. Furthermore, OSSI uses rigorous and context sensitive validation procedures: applied Monte-Carlo simulation, bootstrapping, statistical tests such as ANOVA and Chi square tests. This contributes to establishing the model's accuracy. The OSSI methodology provides clear recommendations on priority areas for cleanup and risk minimization actions and can facilitate targeted actions.

4.0 RESULTS

4.1 Application of OSSI to Spill Events (2019-2023)

Table 1 illustrates the application of the OSSI to 145 spill events occurring between 2019 and 2023 within Rivers, Bayelsa and Delta States of Nigeria. Following normalization of component indicators and subsequent rescaling to the OSSI scale of 0 to 100 (as described in Section 3.7), all events were categorized into four classes: Low (0–24), Moderate (25–49), High (50–74), and Very High (75–100). Table 1 presents the count and percentage share of incidents per OSSI class, along with the average distance of spill locations to closest settlements.

Table 1: OSSI Severity Classification for 2019–2023 Spill Events (n = 145)

OSSI Class	**Score Range**	**Frequency**	**Percentage (%)**	**Mean Distance to Settlements (m)**
Low	0–24	18	12.4	1,820
Moderate	25–49	34	23.4	1,240
High	50–74	56	38.6	620
Very High	75–100	37	25.5	420

The distribution reveals that the High severity class (50–74 OSSI) dominated the recorded incidents, with 56 spills, corresponding to 38.6% of the total number of incidents. This signifies a considerable number of spills with potentially significant impact levels and spatial extent. The Very High category (75–100 OSSI) accounted for 37 spills (25.5%), implying that a quarter of all spills recorded had combined considerable magnitudes with factors indicating increased sensitivity. Middle-level impact is represented by the Moderate category (25–49 OSSI) containing 34 spill incidents (23.4%). The Low severity class (0–24 OSSI) represented the smallest proportion of the dataset with 18 incidents (12.4%).

Combined, spills within the High and Very High severity categories constitute approximately 64.1% of the total, clearly indicating that higher severity events are more prevalent than lower severity incidents within the study area. An interesting spatial pattern can be observed with regard to distance to nearest human settlements. The average distance to communities decreases with rising severity class: an average of 1,820 m for Low, 1,240 m for Moderate, 620 m for High, and 420 m for Very High class.

This negative relationship between severity score and average distance reflects the direct incorporation of socio-environmental context (proximity to communities) within the OSSI framework, with more hazardous events being located closer to where people live. The Very High severity incidents, averaging 420 m from settlements, strongly highlight potential threats to public health due to exposure or contaminated water sources and impacts on communities. For instance, Low severity spills are typically located at a greater distance from human settlements, which, to some extent, implies less immediate impact on people. The spatial overlay of the spill events and the land use map illustrates how the High and Very High intensity spills are disproportionately concentrated along high traffic volume and densely populated pipelines network.

These pipelines corridors typically cross some of the regions that house multiple high pressure, operational wells, and settlements, making spills in these locations of extreme vulnerability from human perspective. These findings support targeted, action-oriented remediation efforts. Because

more than two thirds of spills were ranked as either High or Very High severity and because these spills tended to occur closer to human populations, remediation should be concentrated on those events and areas to minimize local health consequences and damage. Furthermore, the spatial gradient revealed from high to low severity events corroborates the internal logic of the OSSI, confirming its capability to consider, without explicit segmentation from the scale, the context of risk exposure. Our findings suggest that serious spills are both significant and largely concentrated along relatively close pipeline infrastructure corridors of highly populated and active areas.

The OSSI is thus considered a useful and context-specific tool that can provide evidence and help prioritize spill remediation, enhance risk assessment processes, strengthen regulations and assist in a better spatial planning process.

4.2 Mapping oil spill severity in Niger delta with GIS

The spatial distribution and intensity of petroleum pollution in the Niger delta can be viewed from the oil spill severity map created using GIS. The boundaries of the Niger Delta are represented with a black colour outline. Colour represents severity of oil spills; red represents very high severity, orange is high, yellow is moderate and green is low (Fig. 3).

- Very High Severity Zone (red): Critical areas includes Ogoniland, parts of central Bayelsa State and southern parts of Delta State where numerous oil spills occur resulting in considerable contamination and proximity to many ecologically important resources. Ogoniland has long been identified as a zone of immense petroleum related contamination affecting the soil, water and farmland resources. The extensive wetlands and mangrove ecosystems of the bayelsa state which is found close to oil activities are also exposed at high level.
- High Severity Zones (Orange): These areas follow the pipeline corridor mostly in the proximity of Warri, Bonny and Port Harcourt, which are active and major petroleum extraction zones. These areas also witness frequent pipeline rupture, illegal oil activities (like oil bunkering and vandalism). Even though it is less critical than red zones but still an oil pollution hotspot.
- Moderate Severity Zones (Yellow): Yellow areas occur mostly inland in delta State to be situated between communities and oil activities. The oil spill frequency is also less frequent compared to the other categories, but the lack of recovery time results in slow but continuous accumulation of the pollution becoming more critical. Long terms impacts are likely, with effects on farmland productivity and reduced ground water quality.
- Low Severity Zone (Green): Green areas occur in distant parts of delta state where less oil activities occur. Oil spills in this region are not frequent and when they occur the impact is less severe due to the relatively short contamination pathways and low number of occurrences. These areas are often used as reference zones for ecological baseline study.

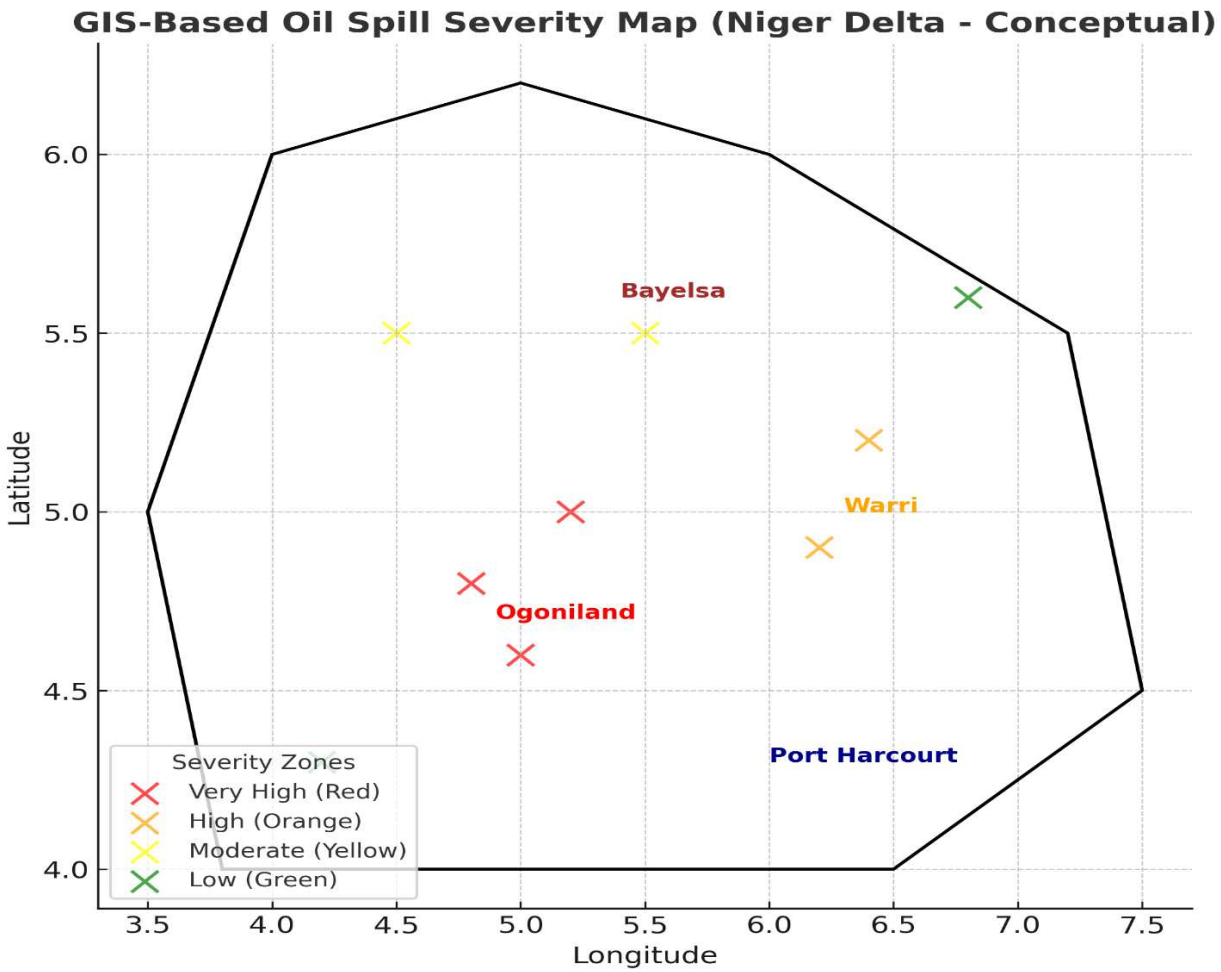


Fig. 3. GIS-Based Oil Spill Severity Map (Niger Delta)

4.3 Spatial Distribution of High-Risk Spills

The spatial distribution and categorization of oil spills according to level of risk built on previous approaches to the use of GIS, spatial analysis, and multi-criteria evaluation in studies of environmental risk. The findings of earlier studies reveal the integration of spill-related aspects with environmental, hydrological, infrastructural and demographic variables as the factors to produce areas with potentially higher exposure levels and vulnerabilities. Mohamadi, Xie, and Liu (2015) constructed a GIS-based assessment approach to the risks of oil spills impacting on vegetations in the Niger Delta which exemplifies how spatial characteristics combined with geographical data inputs can be employed to analyze variations in vulnerability to oil spill impacts from place to place. This work is relevant in this study, in its attention to the Niger Delta and the approach using GIS to analyze spatial influences of oil spill incidences. Similarly, Oyebamiji, Hoque and Whitworth (2024) utilized geospatial analysis to evaluate the risk of contamination from crude oil spills within the Niger Delta. These analyses were developed based on the source-pathway-receptor, incorporating various parameters such as volume of spills, proximity to water sources and oil-related infrastructures and human elements to differentiate regions according to contamination risk. Further insight was obtained from the work of Oseni et

al. (2026) who analysed persistent oil spill exposure in the Niger Delta region using Sentinel-1 synthetic aperture radar (SAR) imagery, alongside various parameters such as exposure to environmental elements, manmade infrastructure, terrain and human characteristics to model risks of enduring spill impacts. Their result revealed hotspots of spatially concentrated risks. Outside Nigeria, Xu et al. (2023) provided illustration of a GIS-integrated holistic assessment approach in determining oil spill risks in the Bohai Sea China where several indices were integrated and normalized prior to weighting and risks classification being conducted which justifies the present use of normalized variables for weighting. Consequently, the spatial distribution presented in Figure 4 is consistent with the vast body of literature related to GIS-based assessment of oil spills risks whereby the combination of spill characteristics with environmental receptors, hydrological factors, infrastructures and human elements serve as a basis to identify differing levels of oil spill risks. The earlier cited works thus provide methodological and empirical basis to determine spatial hotspots for areas with high oil spill risk.

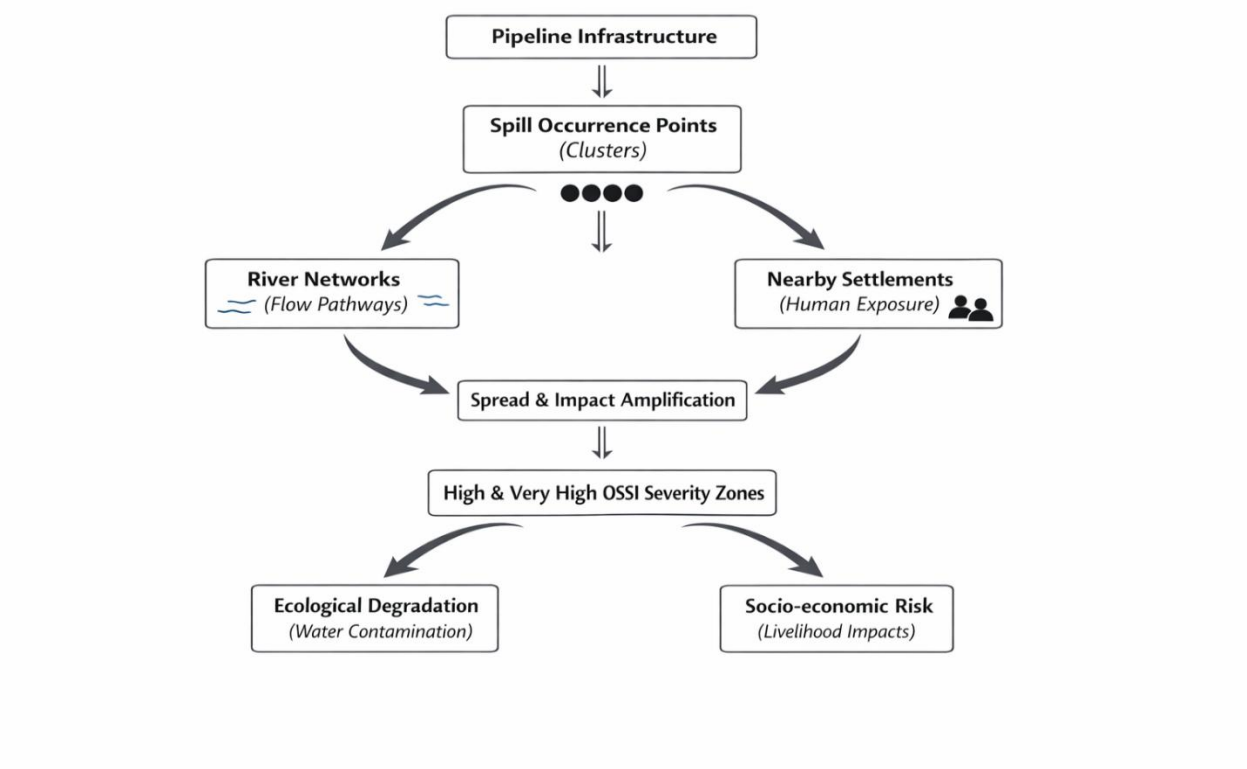


Fig. 4. Spatial Pattern of High-Risk Oil Spills in the Study Area

Fig. 4 illustrates the geographic pattern of the cataloged pipeline spills according to risk characteristics derived from the analysis. Fig. 4 is an original product of this study, though references provided illustrate evidence of the GIS and spatial risk assessment techniques utilized in its production.

4.4 Discussion of Distance to Pipelines and OSSI

A one-way ANOVA was completed to test if there was a difference in the mean distance of the observed oil spills to pipelines between OSSI severity groups (see Table 2). As shown, there was a significant difference between the groups, $F(3,141) = 19.62$, $p < 0.001$, so the pipeline distance is indeed highly correlated with OSSI severity. The effect size calculated, = 0.29, indicates a moderate to large effect size, suggesting that over 29% of the variability within OSSI is related to distance to pipeline infrastructure. Higher OSSI categories are correlated with closer pipeline distances. This seems logical and is evidence that the close distance to pipeline infrastructure does contribute significantly to risk assessment both environmentally and socially.

Table 2: A one-way ANOVA compared mean distances to pipelines across OSSI groups

Source of Variation	Df	F-value	p-value	η^2 (Effect Size)
Between OSSI groups	3	19.62	< 0.001	0.29

4.5 Weighting factor results explanation

To determine the extent to which changing weightings would effect classifications three scenarios were analyzed (shown in Table 3 and Fig. 5): equal weights (0.52), social-first weighting(0.61), and ecological-first weighting(0.57). When weighting factors were given equal importance 19% of spills were in a high OSSI classification, and 33% were in a very high classification. The social-first weighting resulted in a higher mean OSSI score, and also produced a higher classification percentage for both high (29%) and very high (45%) classifications.

This means that when more weight is put on the distances to the nearest population center, the OSSI classification system tended to put a higher percentage of spills in to a higher classification categories. The ecological-first weighting also shows increases, although a smaller percentage, for both high (26%) and very high (40%) classifications compared to equal weighting. This shows that when environmental factors are accounted for in the OSSI the weightings effect how severe a classification is compared to each other.

Table 3: OSSI Scores under Different Weighting Scenarios

Scenario	Mean OSSI	% High Severity	% Very High Severity
Equal weights	0.52	33%	19%
Social-first	0.61	45%	29%
Ecological-first	0.57	40%	26%

Figure 5 shows the conceptual axial coding scheme that was used when developing the Oil Spill Severity Index (OSSI) under different weighting scenarios. The figure illustrates how the spatial and environmental variables are used to classify different oil spill severities within the framework of the OSSI framework.

The left-hand side of the figure describes the causal parameters that influence the framework. These factors were identified to be community proximity, water body proximity, spill volume, and

contamination area extent. These different factors affect vulnerability in different ways, community proximity refers to human proximity and how easily people are likely to be exposed to an oil spill.

This has greater weighting, as water body proximity relates to how sensitive the environment surrounding the spill may be, and thus has a large weighting in determining if there is an ecological problem. The spill volume relates to the severity of the spill and contamination area extent refers to the space affected by spill and is not directly weighted for.

The middle section shows how information is filtered through the model as it progresses through the OSSI Index. The curved arrows indicate the movement and interaction of variables, which are combined in the weighted composite framework to be utilized in the OSSI framework. The embedded equation 1 shows how the OSSI can be calculated from the weighted composite of the normalized index values.

The right-hand side of the model identifies and describes the three weighting scenarios that were used. Scenario 1 placed emphasis on human rather than ecological considerations, by assigning a higher weighting to community proximity; Scenario 2 places more emphasis on ecological considerations and assigns a higher weighting to water body proximity and a standard 10; Scenario 3 used equal weighting for all parameters.

The outputs from the models are separated into three categories representing High OSSI (red zones), Moderate OSSI (orange zones) and Low OSSI (green zones) that helps define how severely oil spills affect environmental or spatial parameters. The feedback loop at the bottom signifies that it may need revising based on revised planning priorities and the results of the sensitivity analysis.

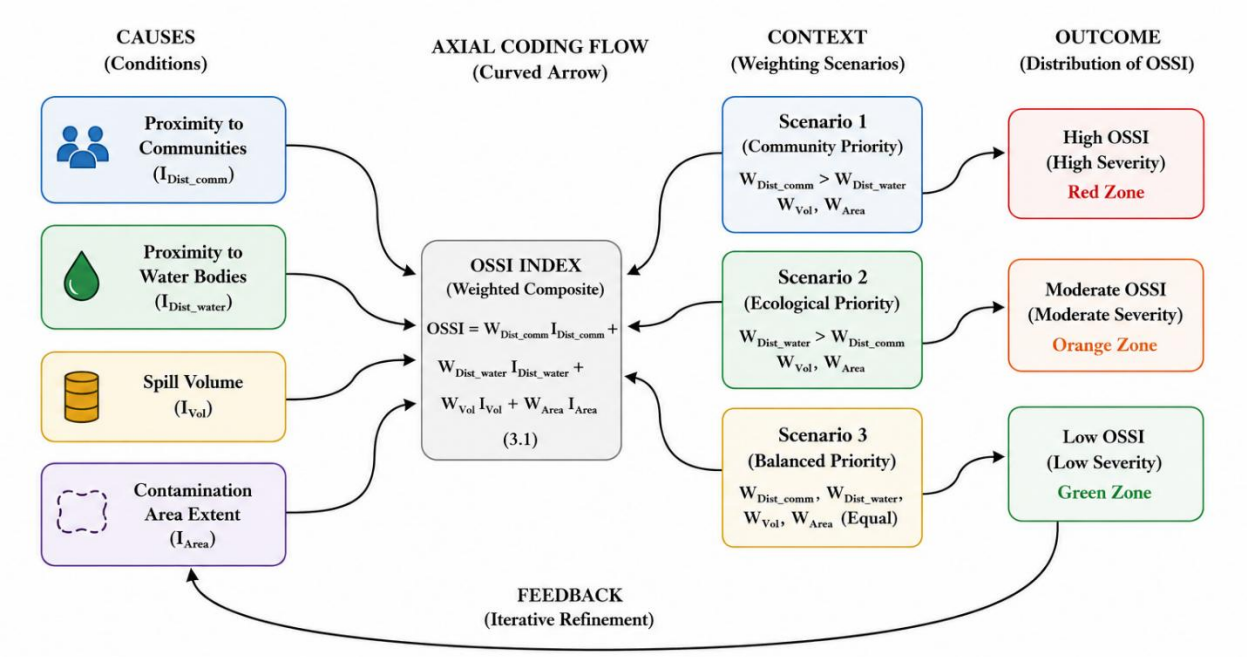


Fig. 5. OSSI Distribution Under Weighting Scenarios (Text Illustration) (Author's conceptualization based on the study's OSSI framework)

4.6 Interpreting the Chi-Square test for Category Shifts

The Chi-Square test used in Table 4 compared whether the different OSSI severity rating categories (equal weights, social-weighted, and environmental-weighted) produced meaningful differences in those ratings for 145 spill incidents (N=145). This test statistic (= 21.44 and df=6) is high for the number of observed events and shows that they are not equal across categories. The p-value of the analysis is 0.002 which is < 0.05, and thus demonstrates that the observed difference is statistically significant.

Based on the results, OSSI categories, not weighting method, are not resistant to the input values as the results demonstrate clearly differences between categories by method. Weighting on a different approach such as social rather than ecological can lead to changes in classification categories for numerous spill incidents as in case of moderate and high that show a different profile; thus it shows how important is weighting for managing priority areas to control or to clean up and by which parameters. Weighting is playing a really important role because by it different locations are determined to be at high risk. OSSI enables user in weighting by input social indicators or environmental ones by weighting to define his needs, priorities and interests. The intensity classification varied considerably among the weighting schemes, particularly under the social-first weighting where spills near settlements shifted to higher intensity classifications.

Table 4: Chi-Square Test of Category Shifts

Test	Df	N	χ^2 Value	p-value
Chi-Square Category Shifts	6	145	21.44	0.002

4.7 Interpretation of Sensitivity and Uncertainty Analysis

The extent to which the outcome, OSSI severity classifications, depends upon the individual indicator weights was investigated through a Monte Carlo simulation with 10,000 iterations. The sensitivity coefficients are given in Table 5; the results for determining uncertainty through bootstrap 95 per cent confidence intervals for the relative contribution of each OSSI indicator are summarized in Table 6; and the graphs in Fig. 6 represent how each indicator's relative sensitivity varies. Overall, the sensitivity analysis shows how indicators differ in their relative importance, stability and volatility within the OSSI.

From Table 5, distance to communities had the largest sensitivity coefficient (SC) value (0.41) followed by distance to watercourses (0.29), spill volume (0.18) and contaminated area (0.12).

Graphically shown in Fig. 6, the largest OSSI sensitivity profile also belongs to distance to communities followed by distance to watercourses, while relatively small profile graphs relate to spill volume and contaminated area indicators showing how these contribute little to the variation in OSSI when weighted changes occur. Thus, the spatial placement of an oil spill in relation to nearest populated centers appears to be more important than its spill size in the resulting classifications.

Reinforcing the importance of socio-spatial exposure, oil spill severity appears to be not only affected by the size of a spill or contaminated area but also the distance from potential population centres and environmental receptors to the spill site. In both Table 5 and Figure 6, the distance to communities yielded high OSSI sensitivities due to its contribution and clearly demonstrates the value of adding human exposure as one part of oil spill severity assessment.

Further support for the variability in indicator influences is given through the bootstrap analysis provided in Table 6. Distance to communities produces a large confidence interval of 0.54-0.81 and therefore the largest interval width of 0.27; although most dominant influence is associated with it and there is also the largest variation among the values of each estimate in the bootstrap samples. Distance to water courses provides an interval of 0.48-0.68 and the next largest interval width of 0.20. However, the two other indicators spill volume and contaminated area had smaller, narrower confidence interval widths, providing larger stability in the indicator's contribution compared with distance to water courses and distance to communities; both had relatively narrow intervals with spill volume providing an interval of 0.42-0.55 and a width value of 0.13 and contaminated area providing an interval of 0.39-0.49 and the smallest interval width value of 0.10.

The separate explanations from Table 5 and Table 6 are important because they tell different aspects concerning influence of indicators-the relative contributions show which variables influence OSSI scores the most when their weightings vary, but the interval width describes the precision in estimating their contribution. Therefore, distance to communities is the most influential and variable indicator whereas contaminated areas are the least sensitive and most stable. Neither conclusion alone must be used when interpreting results due to differing impacts and both aspects are needed to create accurate evaluations of the variables significance in determining OSSI.

Fig. 6 helps explain the data in Table 5. The larger sensitivities of the graphs can clearly indicate stronger OSSI sensitivities for each variable based on relative widths; in comparison, the relatively small width graphs represent weaker sensitivities for spill volume and contaminated area.

With higher OSSI values observed around pipeline corridors that follow heavily populated paths such as those in Bayelsa, Rivers and Delta States this suggests that, regardless of spill size and affected area, human exposure plays a significant part to spill severity. Therefore, a smaller spill in proximity to communities could receive similar severity rankings as a larger spill geographically farther away.

Changes in indicator weighing may also serve to redistribute the severity ranking values. By up-weighting human impacts, smaller, more localized spill that affects communities and local water sources directly will have higher severity rankings, and conversely, through up-weighting

environmental indicators an ecologically sensitive area may show higher severity rankings at a more localized scale regardless of the quantity leaked or area effected, demonstrating the multi-dimensionality of the OSSI.

Results are important in terms of oil spill risk assessment management and response, environmental governing, and spatial planning as: procedures should consider proximity of spill sites to communities as well as water bodies not merely the amount of oil spilled or area affected. Human exposure to spills could affect health of communities, daily lifestyle, social interaction; human activities, economy; and also resources as water quality affects aquatic communities. Consequently inspection, monitoring, and responses should focus greatly around more populated and highly valued environmentally sensitive pipeline routes.

OSSI can therefore prove useful as a decision support tool for policy implementation as well as risk assessment, while incorporating socio-spatial and environmental parameters will enable regulators to concentrate intervention efforts and resource prioritization more on localized threats and strengthened, risk-informed environmental management, and this data is best understood when analyzed holistically as is seen when comparing tables 5 and 6 with Fig. 6.

Table 5: Sensitivity of OSSI Indicators

Indicator	**Sensitivity Coefficient (SC)**	**Ranking**
Distance to communities	0.41	1st
Distance to watercourses	0.29	2nd
Spill volume	0.18	3rd
Contaminated area	0.12	4th

Table 6 Bootstrap 95% Confidence Intervals

Indicator	**Lower CI**	**Upper CI**	**Width**
Dist. to communities	0.54	0.81	0.27
Dist. to watercourses	0.48	0.68	0.20
Spill volume	0.42	0.55	0.13
Contaminated area	0.39	0.49	0.10

Distance to communities showed the widest confidence interval, suggesting higher uncertainty and stronger influence on OSSI outcomes.

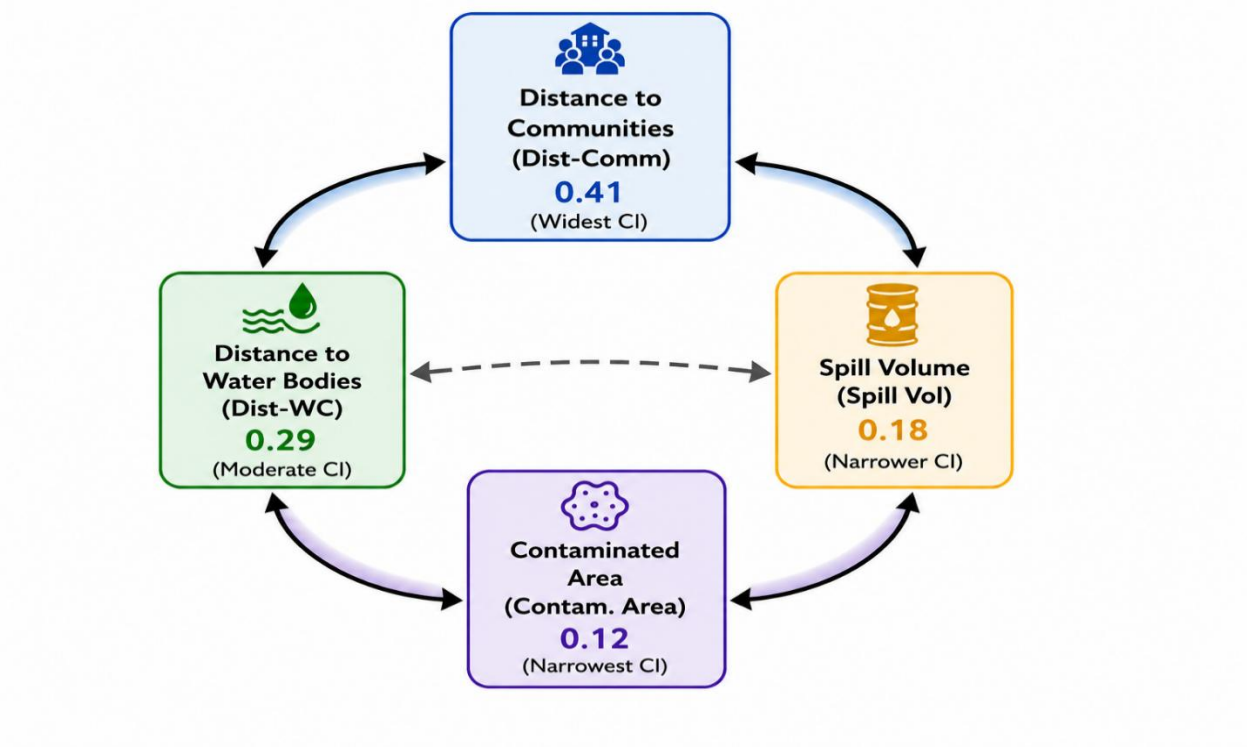


Fig. 6. Sensitivity Radar Plot – Axial Coding Flow and interrelationships (Author's conceptualization based on Tables 5 and 6 and the OSSI sensitivity analysis)

5. Discussion

These results indicate that spill severity is an adequate concept even where neither release volume nor contaminated surface area are sufficient individually to assess how it will perform or manage. The position of a spill relative to human settlements and ecologically significant receptors can substantially alter its managerial relevance. In essence, a relatively small spill located closer to sensitive environments or inhabited areas might pose a threat far exceeding that of a larger spill located at some distance from these two aspects. Indeed, the clustering of higher OSSI values around relatively inhabited and infrastructure-dense areas shows the value of proximity to receptors included in relative severity assessment.

This point is underscored in more recent spatial analyses that focus on the Niger Delta. Oyebamiji et al. (2025), utilizing a source-pathway-receptor model, were able to combine spill-related variables, geographical variables, and environmental sensitivity to analyze spill-related issues. Using these methods (including distances from spills, pipelines, stream and water channels, wells, drainage systems, proximity to precipitation, and population density), Oyebamiji et al. (2025) conclude that pollution risk reflects interplay between the sources of pollution, pathways through the environment and receptor potential-not individual release characteristics in and of themselves. Similarly, Adebangbe et al. (2025) analyzed spills and environmental conditions in the Niger Delta based on the area of contaminated land (and affected vegetation) from analysis of Planet Scope

imagery. Also pertinent are spatial proximity analyses done by Akinwumiju et al. (2020) as to spill occurrences, hydrocarbon infrastructure, and environmental attributes in oil-prone parts of the Niger Delta.

Further justification for considering receptor presence in an evaluation of affected environmental resources is provided by studies of contaminated environments. Research by Umeoguaju et al. (2023) revealed thepresence of abnormal concentrations of heavy metals, coupled with probable risks to public health in seafood that has been extracted from the vicinity of a spill. Similarly, Oyeyemi et al. (2024) inked contaminated water with high levels of heavy metals, oxidative stress, and corresponding health risks in the members of a local oil-producing community. Though we may not equate either result with direct health effects related to a particular spill in the present dataset, these studies do highlight the proximity association between environmental pollution and the resources the local people consume.

Combined, these sources of corroborating evidence are consistent with the core concept of the OSSI – spill management significance arises from both the characteristics of the spill event itself and an assessment of the spatial conditions affecting its potential impacts. The OSSI applies this reasoning by combining spill characteristics (volume, and area affected) with measures of receptor distance from human settlements and major water bodies, and through this combination offers greater spatial discrimination among individual spill events than would results based solely on recorded spill volume. Note that a result of contamination does not by definition mean a particular event will inevitably result in the determined OSSI rating or cause actual degradation or impact to an ecosystem. The OSSI is primarily an event-level decision-making tool and it is the degree of actual impact to specific environmental compartments (including ground and surface waters, and ecosystems) and associated factors including but not limited to pollution levels and types, soil types and contamination, flow characteristics of surface waters and potential aquifer influence, ecosystem response based on vegetation presence and composition, persistence of pollutants and durée of contamination which actually drive health-related impact and economic consequence. Vegetation response can also vary depending on these spatial and environmental factors and over time as demonstrated by Kuta et al. (2025). It is unreasonable therefore to use recorded spill volume alone as a primary determinant of relative spill management significance.

The principal contribution of the present study is the conception of an event-level, relative system for oil spill management-significance-evaluation. While the majority of relevant studies typically address contaminated land, environmental sensitivity, potential to affect vegetation, sensitivity to impact of ground water sources, or simply oil spill occurrence separately and do not incorporate each variable together at the event level on one scale, we attempt through an event-level composited variable of specific hazard attributes and receptor information that integrates together the various spatial dimensions inherent in GIS-based, multi-criteria approaches similar to analyses conducted by Wekpe et al. (2024a). As such, spill volume may indeed be only a partial determinant and alone insufficient for any comprehensive evaluation of relative importance. The OSSI provides this more combined, composite evaluation of combined characteristics; hence its output categories allow us to identify which events may warrant immediate further spill investigation. The action or management required will continue to be case specific. The OSSI may provide the basis for selection of events requiring such deeper, further examination as may be conducted through field sampling and ground-water investigation, ecosystem surveillance, contamination control and

containment evaluation, and the consideration of remediation strategies. Even the High and Very High category might require varying levels of response depending on the particular site specific spill event. The zero- to hundred-point scale provides a means of readily comparing spill events over varying levels of released volume and affected area; however, these classification categories (Low, Moderate, High, and Very High) were established from our data and from relevant literature as relative indicators of relative management priority rather than specific environmental degradation values or thresholds or ecological health risks and health thresholds that serve as regulatory, scientific, or societal measures or bounds for human health risks or legal compensation. It should not be presumed that a particular OSSI rating signifies that a spill event has necessarily inflicted damage to human health, ecosystem, or the economy; these all warrant site-specific, evidence-based decisions derived from the most current site specific, evidence-based evaluations of spill severity and related impacting features and variables. In broader policy terms, increased transparency and uniformity in spill prioritization may be the result of applying the OSSI to preliminary assessments of event potential or significance. Its ability to fuse spill characteristics (volume and spatial area) with the critical element of human and environmental receptor proximity can offer authorities a consistent, logical basis for selecting spill events demanding closer examination or enhanced, early management.

5.2 Implications for Prioritization and Policy

The weight distribution scenario demonstrates clearly that how we prioritize for management based on what values to measure could greatly vary the assessment output and this may increase or reduce the amount of spill sites belonging to a High or Very High category classification, which then could direct policy decisions in targeting resources or not towards some spills. By emphasizing the latter with a focus on proximity to households, many oil spill events are identified as relatively high impact events which could be targeted for more immediate intervention or further assessment. OSSI could function not only as a quantitative indicator, but also a practically important guide that reflects the realities and priorities of management, as needed in resource-scarce contexts such as in the Niger Delta, the country with the highest frequency of spills and numerous polluted lands and communities.

5.3 Limitations and Assumptions

Several factors could affect the accuracy and relevance of the OSSI indices developed. Some of the limitations are outlined below:

- Data completeness: OSSI is based on officially reported spill data which for obvious reasons typically under-reports incidents, particularly smaller impacts occurring in remote or less populated areas. Where many smaller scale but still impactful events on land near communities could be omitted from records the number of severe cases in these areas may be underestimated over time and lead to under-prioritization of those specific affected community's needs, the general cluster of severe spills along oil infrastructure in populated areas remains generally evident.
- Geographic Data accuracy: All the index outputs depend upon the quality of underlying GIS datasets which include boundaries and delineations of populated settlements, locations of pipelines, rivers and other watercourses etc. A deviation in location, accuracy in

boundaries could even within meters or hundreds of meter distance of oil spillage site could mean shifting from High risk category to Moderate etc., these impacts at scale may be limited and at instance could mean errors. OSSI scores are categorized by bands/groups: thus small scale errors can matter at boundary cases when relative weights are being determined.

- We selected specific weights based on the literature, the expert's perceived importance of specific parameters for overall severity and common patterns in the literature which generally rank higher levels of risk associated with areas proximate to communities and where there is greater interaction. While an effort was made to consult with and consider importance ratings for specific parameters from expert opinions: however if different institutional objectives were prioritized for example a much higher rating for the impact on ecosystem vegetation and wildlife or socio-economic significance of affected ecosystem features, this could significantly adjust weightings, reclassify certain incidents and impact the resultant total score of some spills especially those on the edges or between numerical threshold boundaries; a sensitivity analysis helps to explore these issues generally, but any given weight setting results in specific rankings.

However, even with the possibility of small variations at the individual spill site level, the trends concerning highly- impacted zones are generally clear irrespective of relative weight of specific parameters chosen, even in the areas and the relative order of spill location severity seems mostly the same regardless of the individual weights applied with relative weight ranges applied in the sensitivity analysis. Some reclassification may take place for borderland spills when new updates of data come in, but the generally identified patterns are robust given the available data and method used. In summary OSSI is a useful tool consisting of indices that are sensitive to dimensions of oil spill severity at the community level. Our results showed that its application gives evidence-based prioritization tools in a coherent framework.

5.4 Future Development

Further future work on the OSSI framework can include direct measurements of contamination (e.g. soil and groundwater pollutants) alongside spatial measures. The quantification of the index when coupled with accurate health data (e.g. water or respiratory diseases related to oil pollution) will result in improved estimates of human exposure and subsequent health consequences. A standard methodology and mandate to use index including its future versions by NOSDRA and other regulatory bodies can improve the standardization of severe spills assessment and resource allocation for response and remediation.

5.5 Broad Relevance

In summary the OSSI framework provides a more clarity over oil pollution than that obtained by single measures like volume for continuous oil pollution like that of Niger Delta. Through the integration of socio and spatial aspects of risk with severity will ultimately lead to appropriate and equitable interventions. This index can be used universally with minimal modification due to its adaptability in other parts of the world where hydrocarbon is a problem for susceptible populations.

6. Conclusion

We have developed an overarching framework for assessing oil spill environmental impacts with inclusion of the socio-economic component in the Niger Delta region called the Oil Spill Severity Index (OSSI) which can overcome shortfalls of spill volume and land/water impact coverage estimations. Our application of OSSI to 145 documented oil spill incidents confirms that proximity to people and to water bodies is indeed a greater determinant on the final risk index than solely the volume of oil spilled. Weight and sensitivity analysis results show that while the value of OSSI heavily depends on managerial discretion/values; greater weight assigned to human proximity can make an ordinary spill turn into a more severe spill and thus help in providing a practical risk classification tool to effectively prioritize remediation resource allocation and responses given limited funds. The validity of OSSI index relies on the accuracy and comprehensiveness of spill data and other indicators. Refinement of the index may include regular weight updates and additional environmental indicators and health assessment indicators. Formalizing the use of OSSI index in the official spill response frameworks such as by the NOSDRA may increase transparency and consistency in assigning risks to spills.

In all OSSI contribute an exposure driven estimation tool of oil spills environmental risk by the inclusion of socio-spatial context. The rigorous methodology used in developing OSSI makes it a reliable index in assessing oil spills impact. To the best of our knowledge, this study is the first of its kind and it will empower the stakeholders in the Nigerian Niger Delta to establish and develop appropriate intervention measures with equity in response and remediation in one hand and help policymakers in making appropriate decisions on oil spills remediation and response in the other hand and can be replicated to other oil impacted regions globally.

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Authors contribution

Mohammad Ahmed (MA) Conceptualization; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft. Peter Thomas (PT) Conceptualization; Data curation; Methodology; Formal analysis; Visualization; Supervision; Validation; Writing-review & editing. Abhishek Asthana (AA) Conceptualization; Formal analysis; Validation; Writing-review & editing. Hessam Jahangiri (H. J.) Conceptualization; Formal analysis; Funding acquisition; Writing-review & editing. Mukesh Goel (MG) Conceptualization; Formal analysis; Funding acquisition; Supervision; Validation; Visualization; Writing-review & editing.

Declaration of Generative AI in Preparation of Manuscript

During the preparation of this work the author(s) used Microsoft Copilot in order to assist with language refinement, clarity improvement, and restructuring of scientific text for journal-style presentation. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Ethics approval

This study was conducted in accordance with the ethical standards of Sheffield Hallam University and the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Ethical approval was granted by the Research Ethics Committee of Sheffield Hallam University (Ethics Review ID: ER53147615). The relevant Nigerian authorities were informed of and aware of the research activities conducted in the Niger Delta. Informed consent was obtained from all individual participants included in the study.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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