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Modelling of Potential Pipeline Impact Radius and High Consequence Area in a Wetland Sub-Region of Nigeria

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Abstract

Crude oil transportation through pipelines presents danger to communities along its path. In the Niger Delta region of Nigeria for instance, pipeline vandalism occurs indiscriminately and regularly, such that every segment of a pipeline network becomes a potential target and possibly source of oil spill hazard. In terms of pipeline hazard and risk distribution, the oil plume's ability to migrate freely in wetlands and encroachment on pipeline right of ways by people increases chances of wider contact and exposure opportunities to inhabitants and the environment. Despite several efforts to mitigate pipeline hazards in the oil and gas sector, none has been effective in Nigeria partly due to paucity of data in public domain and poor public participation. Therefore considering the environmental and human health challenges associated with oil spills, an alternative method was developed using multi-criteria decision analysis to model 1) pipeline hazard zones, 2) potential pipeline impact radius, and 3) high consequence areas with four attribute layers, *i.e.* land cover, population, river and pipeline to encourage public participation. The model identified land use areas, communities and rivers likely to be susceptible to pipeline hazards and areas requiring regular monitoring and possible intervention. Meanwhile the model sensitivity test indicated that the river layer was most sensitive, while transferability was limited to similar criteria variables. The model can stimulate public participation in pipeline hazard management while policy makers and regulators would find it relevant in oil spill impact mitigation.

Keywords

Model, Spatial Analysis, Pipeline Hazard, Exposure Pathways, Oil Spill Risk

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1. Introduction

Pipeline accidents are caused by mechanical and operational failure, natural hazard and third party interference [1] [2]. Nigeria has recorded unprecedented number of these failures mostly from human interference and production error, for instance Shell Petroleum Development Company (SPDC) Nigeria reported an average of 200 oil spill incidents every year since 2005 [3]. Since the degree of risk is the product of the probability and consequence of pipeline rupture [4], the higher the probability of oil spill risk is, the higher the chances of exposure and impact on human health and the environment are. **Table 1** shows that Nigeria has high tendency (risk) of pipeline failures compared with other regions, in fact [5] alluded to the existence of gangs that specialises in vandalising oil pipelines in the area.

Pipelines are important components of crude oil transportation and even play significant role in shaping political and economic landscape of global energy supply and transmission [2] [6]. To this end, extensive network of pipelines has been constructed to facilitate transportation of oil and gas across political boundaries. As a result, several thousand kilometers of these pipelines traverse oil producing regions collecting, distributing and redistributing large quantities of crude oil across the world [1] despite its attendant negative impact on the environment. In order to mitigate the impact of oil pipeline spills on human health and the environment, the concept of pipeline impact radius (PIR) and high consequence area (HCA) was developed to delineate areas likely to be affected by pipeline hazards [7] [8].

1.1. Pipeline Impact Radius (PIR)

According to the Pipeline and Hazardous Material Safety Administration (PHMSA) of the US Department of Transportation, discharge from pipeline failure can affect human health and safety; it can also cause environmental degradation and damage to properties. As a result, experts in pipeline safety developed the concept of "pipeline Impact Radius" and "High Consequence Area" to determine places where pipeline hazard can cause significant adverse effect. Thus, a designated PIR buffer is an estimated distance beyond which humans and ecological receptors have about 90% chance of survival [8]. The PIR is derived from pipeline properties (*i.e.* size, diameter, pressure, etc.) using Equation (1) to delineate areas where pipeline accidents can cause adverse effects [4] [8] [9] and beyond which humans and ecological receptors could be least affected [8].

$$r = 0.69 \times \sqrt{pp \times pd} \tag{1}$$

where: r = impact radius in feet, pp = pipe pressure in pound per square inch, pd = is pipe diameter in inches, and 0.69 = a constant for natural gas.

The United States Pipeline Safety and Regulatory Certainty Act of 2011, require operators to maintain up-to-date record of pipelines in high consequence area (HCAs) by calculating PIRs along their pipelines, and identifying the population within the impact radius [9]. HCAs are potential impact circles containing structures intended for human occupancy or outdoor areas occupied by people. **Figure 1** shows a typical PIR and HCA de-

Table 1. Pipeline failure in Nigeria with other regions of the world.

Region	Product	Failure Rate 1000 km/year	Year
United States	Gas	1.18	1984-1992
United States	Oil	0.56 - 1.38	1984-1992
Europe	Gas	1.85	1984-1992
Europe	Oil	0.83	1984-1992
Western Europe	Oil	0.43	1991-1995
Western Europe	Gas	0.48	1971-1997
Canada	Oil & Gas	0.35	N/A
Hungary	Oil & Gas	4.03	N/A
Nigeria	Oil	6.4	1976-1995
Niger Delta (Nigeria)*	Oil	1.14	1999-2005

*Achebe *et al.* (2012).

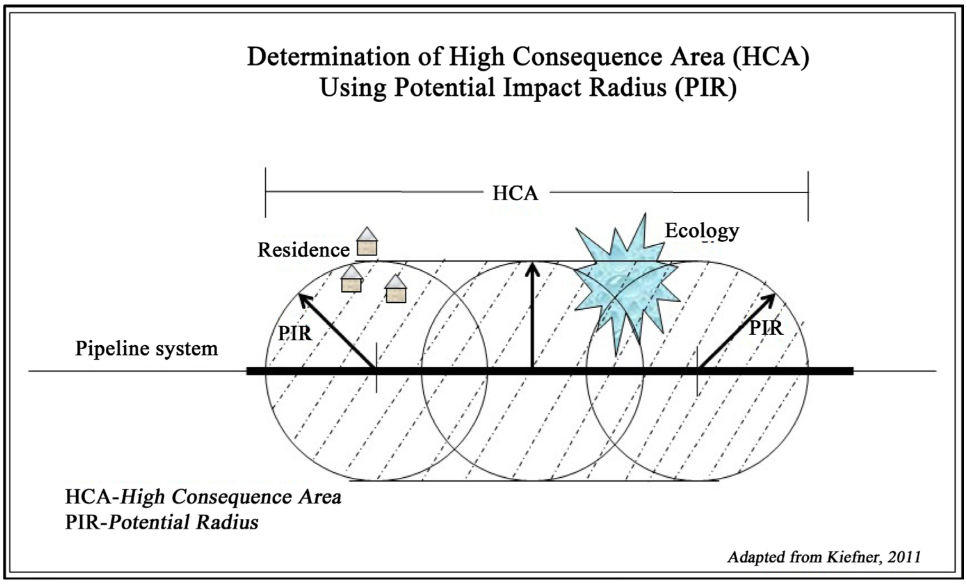


Figure 1. Illustration of PIR and HCA delineation (after [9]).

marcation representing areas where population, source of domestic water and sensitive ecological resources intersect with the PIR. Thus for proper designation of areas of concern, the US Department of Transportation employs "HCA" to describe potential impact areas located within pipelines buffers.

In this paper, an alternative method is developed with Multi-Criteria Decision Analysis in the context of Analytical Hierarchy Process (MCDA-AHP) to model potential risk area and compensate for data paucity, because pipeline data are not easily obtainable in the public domain in Nigeria, this has hindered public participation and scrutiny of pipeline operating standards in the country [10]. This model provides framework for public participation in and for independent determination of Potential Pipeline Impact Radius (PPIR). Developed as an automated model, users can extract, store and update information of communities susceptible to pipeline hazards for community-based risk assessment and environmental management.

1.2. MCDA Method with GIS

The integration of Multi-Criteria Decision Analysis (MCDA) method in GIS has improved conventional method of map overlay in decision analysis [11] for spatial and non-spatial data transformation. MCDA is a problem-solving procedure in which a set of alternative decisions are evaluated on the basis of conflicting criteria [11]-[13]. The method emerged from economic planning in the early 1970s [14] to help decision makers solve problems by introducing qualitative technique in data analysis [15], based on scientific or subjective, certainty or uncertainty, deterministic or probabilistic approach in evaluating conflicting alternatives [11] [16]. Each alternative is evaluated against a set of measurable criteria e.g. yes/no, or present/absent [17] and transformed so that results and participation is transparent [18]. Thus MCDA provide decision makers with the capacity to make decisions using past (experience) and present information to predict future outcomes [11] [19] and manage potential future risks, and/or vulnerability to natural hazards [19]. MCDA is divided into Multi-Attribute and Multi-Objective Decision Making base on single and multiple decision problems that are differentiated by the classification of criteria into either attribute[1] or objective[2] decisions. The multi-objective is mathematically oriented and continuous (*i.e.* assuming the best solution to be among the alternatives), while the multi-attribute is data oriented; discrete and predetermined *i.e.* it has limited number of alternatives [11] [13] [16]. This paper adopted the Multi-Attribute (discrete) approach to measure and qualifies spatial entities representing "*element of a real-world… system*" [11].

Over the years the multi-attribute method is integrated in GIS using Weighted Linear Combination (WLC)

[1]An attributes are properties of elements of a real-world geographic system; they are measurable quantity or quality of a geographic entity or a relationship between geographic entities.

[2]An objective is a statement about a desired condition under consideration, an indication of the direction of improvement for one or more attributes.

[20] [21], ideal point methods [11] [22], concordance analysis [23], and analytical hierarchy process (AHP) [24] [25]. The capability of GIS to perform data acquisition, storage, retrieval, manipulation and analysis, and the capability of MCDA to combine geospatial data and decision-makers preference into one (alternative) coherent decision making system makes it relevant in geo-spatial analysis [15]. In this paper, WLC in the context of AHP was used; WLC combines Boolean operators like intersection (AND) and union (OR) to perform weighted averaging and weight allocation of relative importance to attributes in a map layer [11] [26] and scores for individual alternatives to ascertain the alternative (attribute) with the highest weight [17]. The AHP technique developed by [27] allows experts develop prioritization strategies for adjudging criteria and alternatives [27]-[30] that best contribute to achieving set goals and objectives.

The AHP method drives weight for attribute layers in combination with other attributes [24], and aggregate prioritise on each level of the hierarchy so that corresponding criteria weights can be determined [18] [31]-[33]. The application of MCDA in GIS follows these steps:

1) *Criteria selection*: identification of relevant data layers for problem solving, which can be presented in thematic layers of specific features and attributes.
2) *Criterion score standardization*: allow data to be measured on similar unit or scale. By standardization, the data layers are converted to comparable units so that beneficial factors can be presented "*on a scale that gives high value to high benefit and low value to low benefit*" [34].
3) *Weight allocation*: reflects relative importance of the layer to a specified goal and objective e.g. Allocation of the highest weight to an attribute considered most important/significant.

1.3. MCDA for Pipeline Risk

The application of analytical methods involving human behaviour, socio-economic and environmental factors in decision making are integrated in geospatial analysis using MCDA to evaluate geographically define alternatives [11] [22] [35]-[37] applied multi-criteria spatial decision tool to identify potential conflict areas linked to oil and gas production on the coast of Texas. The study identified sites with least contention for oil and gas production and activities within a leased tracts, and for selecting comparative advantageous landfill sites according to specified factors [32] [38] [39]. Because pipelines are very useful for transporting oil and gas, they also present serious risk to the environment, as such, MCDA/AHP was applied in identifying and estimating some of the risks [40]-[42]. Although there is lack of consensus among researchers and professionals on the best mode of assessing pipeline-associated risks [43]-[45] developed an integrated framework using AHP and MCDA technique to assess cross-country pipelines based on technical, socio-economic and environmental alternatives for oil pipeline construction in India. Good pipeline system integrity management depend on monitoring, detection, and maintenance of deteriorating pipelines.

To improve this, [42] developed a fuzzy multicriteria analysis for selecting the best biosensor designed appropriately for a targeted analyte and micro-environment for prompt and reliable leak detection. Eventhough pipelines are said to be safer and very economical for transporting bulk liquid (especially oil and gas), the catastrophic consequences associated with pipeline accidents motivated [41] to propose a multicriteria decision model using multi-attribute utility theory to incorporate decision makers' behaviour in assessing human, financial and evnironmental risk dimensions in a multidimensional risk assessment framework for pipelines transporting hydrogen. In a similar approach [40] developed a risk-based ranking of natural gas pipelines into segments using the multi-attribute utility theory, while [46] incorporated the decision maker's preference in decision structure using MCDA to assess risk in hydrogen pipelines also by ranking pipeline segments in terms of risk. [30] on the other hand developed a decision-based method for managing oil and gas pipeline risks, using the MCDA framework and AHP to prioritise pipelines for design, construction, inspection and maintenance.

2. Study Area

The paper investigated network of major oil pipelines in the Degema oil field area of south-western part of Rivers state of Nigeria. The area covers approximately 1939 km^2 with about 374 communities and a population of around 1.26 million distributed across eight (8) local government areas of the state *i.e.* Abua/Odual, Akuku Toru, Asari Toru, Degema, Emuoha, Portharcourt, Okirika and Obio/Akpor. The land is generally between 2 to 5 meters above sea level and the vegetation comprises of mangrove forests and fresh water swamps. It is a wetland area with several parts exhibiting seasonal inundation during raining seasons (**Figure 3(a)**).

3. Materials and Methods

3.1. Dataset and Criteria Selection

A SPOT satellite image of the area was obtained for generating spatial datasets through onscreen digitisation and supervised classification in ArcGIS 10. Community point and boundary shapefiles was obtained from commercial vendors in Lagos state, Nigeria while population data was collected from the National Population Commission also in Nigeria for the purpose of the paper. The criteria/alternatives considered relevant for achieving the goal of the paper, which was to delineate pipeline impact and hazard areas in the study area. The identified objectives were 1) source of impact (oil facility) and 2) land-use land cover attributes, from these alternatives like a) proximity to pipeline, b) proximity to river, c) land cover and d) population density were derived to highlight the existence of pollutant linkages and potential risk of exposure to pipeline hazard.

The methodology for the model is outline in **Figure 2** in conformity with procedure and components of the analytical hierarchy process (AHP). The alternative/attribute layers were selected on the basis of data availability and significance in rural land use exposure scenarios described in **Table 2**.

The first step in the AHP process is the 1) AHP hierarchical design, 2) pairwise comparison of elements, and 3) priority rating/ranking [24]. The pairwise comparison method incorporates a ratio matrix [11] [27] [29] to assign relative score according to comparative importance on the basis of "less to more importance" using Saaty's scale (**Table 3**).

3.2. Factors and Constraints Consideration

A factor is a deliberate condition imposed on a variable to enhance its capability to satisfy established goal or

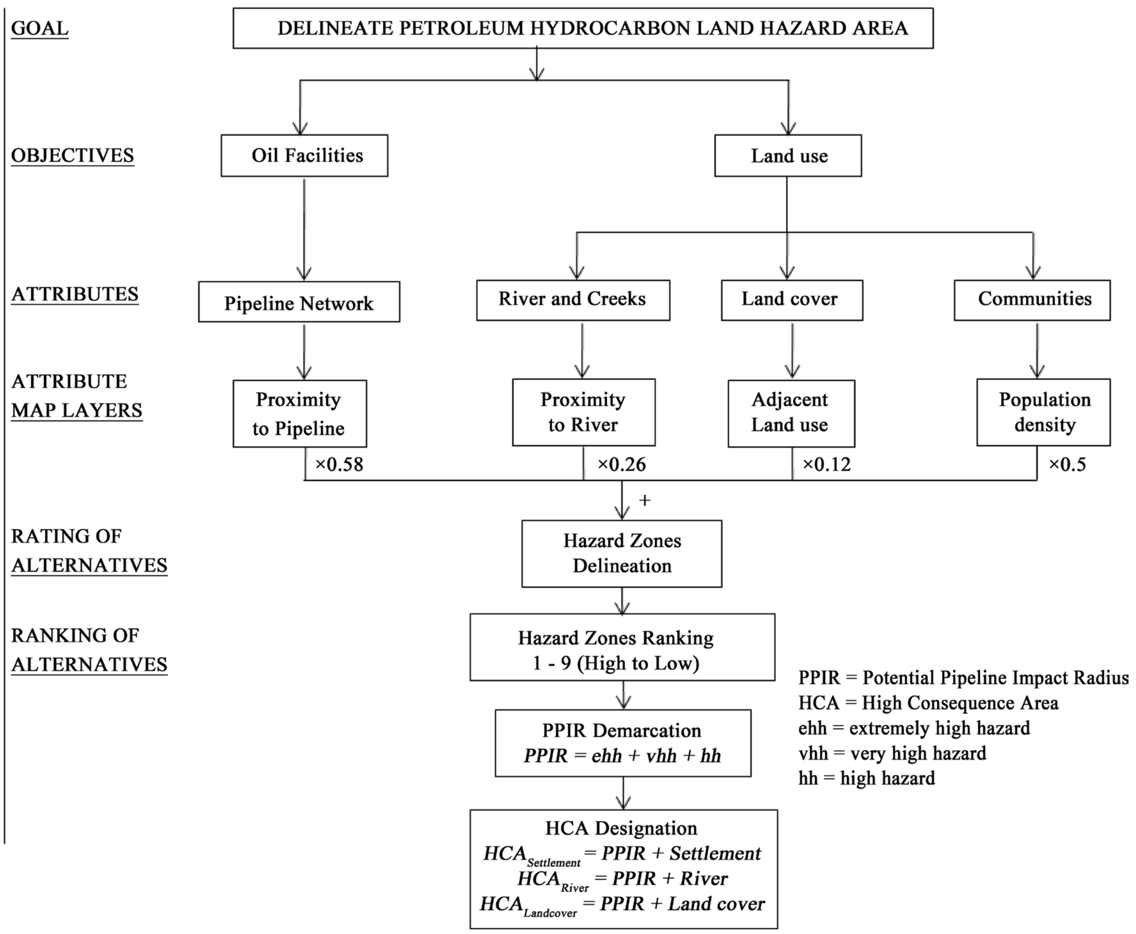


Figure 2. Analytical hierarchy process component layout of the model.

objective, while constraint is a condition imposed on a variable to limit its ability to satisfy the same goal or objective. For example, conditions excluding an area based on distance, absence, or availability of a feature. The constraint and factor conditions delimiting proximity of pipelines, river, population (settlements), and land cover to source of hydrocarbons discharge are listed in **Table 4**. To meet the requirement, a 4 km distance buffer was imposed to represent the average distance people may travel to perform outdoor land use activities [47] or the farthest distance covered before coming in contact with a pipeline. Thus since pipeline failure can occur on any segment of the pipeline network (**Figure 3(b)**), the entire network was therefore considered a potential source of hazard (oil spill).

4. Data Analysis

4.1. Pairwise Comparison and Weight Allocation

Weights were allocated via pairwise comparison matrix in **Table 5** by comparing relative significance of individual criterion to determine the most significant to the objective. The less significant criterion was rated 1 and the most significant was rated 9 in accordance with Saaty's scale (**Table 3**) of preference [30] [48]. Although there are other techniques for assigning weights, the pairwise matrix developed in the context of AHP was chosen because of its ease and wider application in multicriteria decision analysis (MCDA) studies. The application of weighted linear combination in GIS spatial decision and MCDA requires normalisation of criterion weights to the same unit so that variables can be compared on a similar scale [11] [20]. In this study, criterion layers were ranked to reflect their significance in land-use exposure scenarios base on expert elucidation and experience of a focus group.

In allocating the weights, values in each column was summed and used to generate normalised score for criterion in stage 2 of **Table 5** based on Example 1. Stage 3 in **Table 6** determines calculated weights by eigenvectors.

Table 2. Attributes and attribute layers used in the modelling.

SNo.	Map layer	Description
1	Land cover (Supervised Classification)	This represents the natural vegetation and land resources available for land-use benefits, consists of mangrove forest, forested fresh water swamp, rain-fed agriculture land, grazing field etc. (**Figure 3(a)**).
2	Pipeline(Digitisation)	This consists of series of connected pipelines used to transport crude oil to various destinations, represents the main source of petroleum hydrocarbon discharge in the area (**Figure 3(b)**).
3	Communities (Supervised classification)	Is used as a surrogate for population distribution marked in point density describing population distribution per square kilometer (**Figure 3(c)**).
4	Rivers and creeks (Supervised classification)	This represents the major and minor rivers (creeks). River (water) transport a common means of transportation and source of domestic water supply and other economic purposes like fishing. This layer is an important variable in the socio-economic life of the rural Niger Delta and yet it influences the migratory capacity of oil spills (**Figure 3(d)**).

Table 3. Saaty's pairwise comparison scale [11].

Degree of importance/significance of attributes								
Equal	Equal to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Very to extremely strong	Extremely strong
1	2	3	4	5	6	7	8	9

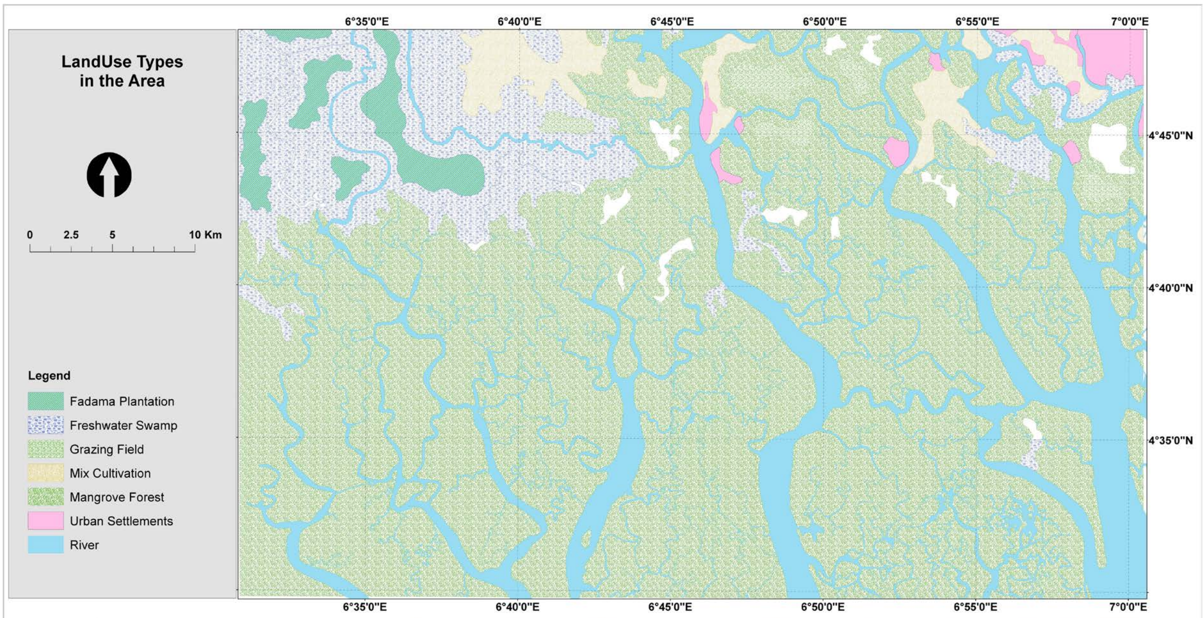
Table 4. Factors and constraint parameters.

Criterion	Table column head		
	Factor (in)	Constraint (out)	Procedure
Proximity to pipeline	≤4 km	>4 km	Buffer at 0.5 km interval
Proximity to river	≤4 km	>4 km	Buffer at 0.5 km interval
Land cover	N/A	N/A	All land cover
Population	N/A	N/A	Point density

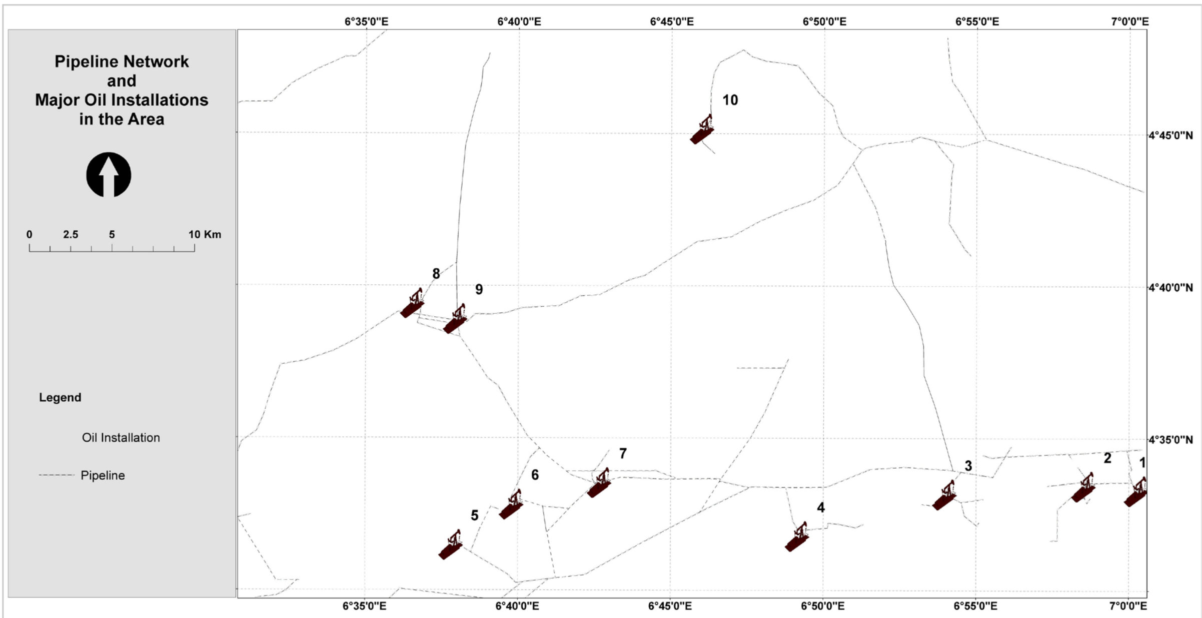
Table 5. Pairwise comparison matrix and weight derivation.

Criterion	Stage 1: Score				Stage 2: Standardisation			
	PP	PR	LC	P	PP	PR	LC	P
Proximity to pipeline (PP)	1	3	5	9	0.61	0.66	0.54	0.50
Proximity to river (PR)	1/3	1	3	5	0.20	0.22	0.32	0.28
Land cover (LC)	1/5	1/3	1	3	0.12	0.07	0.11	0.17
Population (P)	1/9	1/5	1/3	1	0.07	0.04	0.04	0.06
Total	**1.64**	**4.53**	**9.33**	**18**	**1.00**	**1.00**	**1.00**	**1.00**

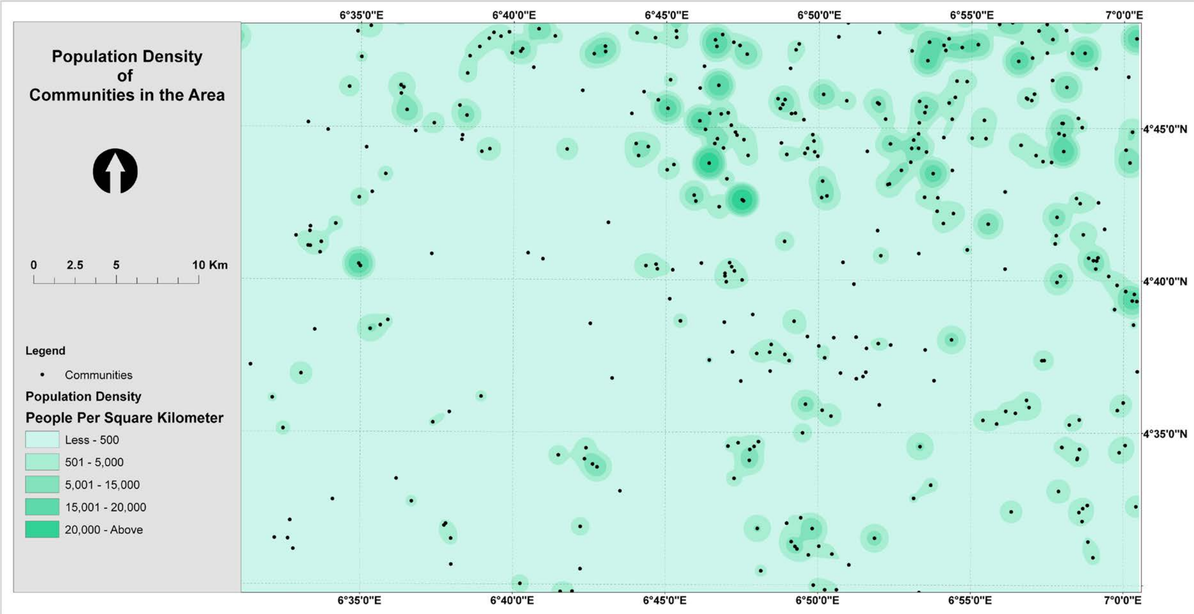
Example 1:1/1.64 = 0.61. (Stage 2).



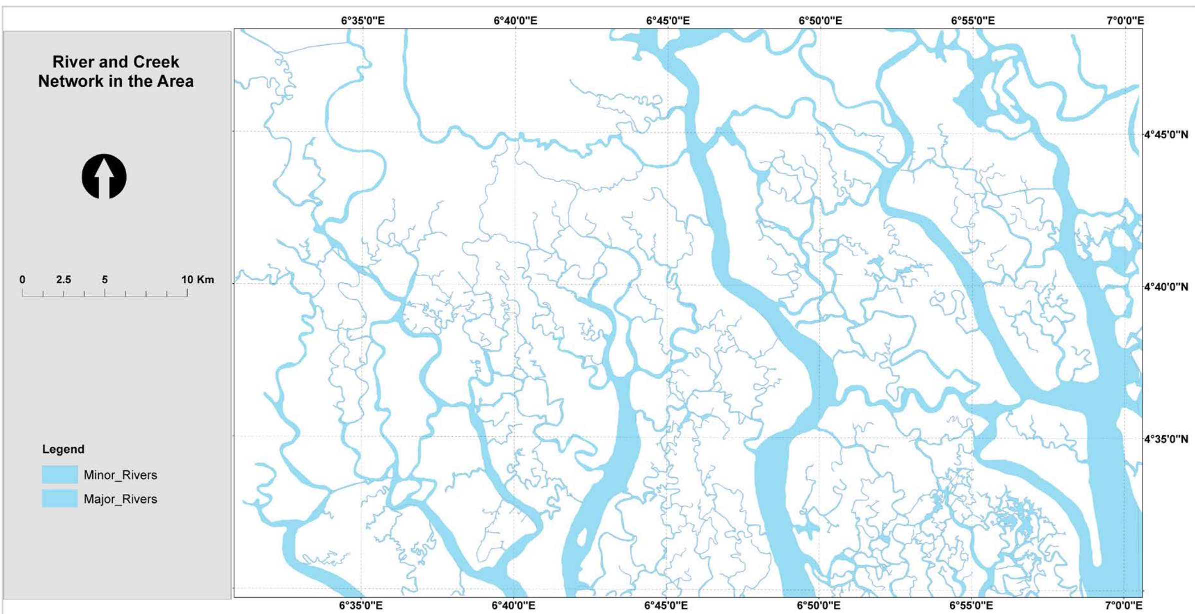
(a)



(b)



(c)



(d)

Figure 3. Thematic map layers used for the MCDA modelling (generated by authors, 2014). (a) Vegetation and land cover; (b) Pipeline network; (c) Population and community distribution; (d) River network.

Table 6. Weights determination and allocation.

Criterion	Stage 3: weight calculation	Weight
Proximity to pipeline (PP)	[0.61 + 0.66 + 0.54 + 0.50]/4	0.58
Proximity to river (PR)	[0.02 + 0.22 + 0.32 + 0.28]/4	0.26
Land cover (LC)	[0.12 + 0.07 + 0.11 + 0.17]/4	0.12
Population (P)	[0.07 + 0.04 + 0.04 + 0.06]/4	0.05
	Total	**1.00**

4.2. Determination of Consistency Ratio (CR)

The CR is determined by dividing consistency index (CI) by number of criteria (n), thus if the RI value is greater than the RI allocated to particular number of criteria, the weight allocation is considered inconsistent. Random inconsistency (RI) is an index for measuring the consistency of weight allocation. A good CR for 4 criteria according to [11] must have RI not more than 0.9 (**Table 7**). **Table 8** shows process of CR determination for the four criteria.

$$\text{Consistency Index }(\text{CI}) = \frac{\lambda - n}{n-1} \tag{2}$$

Lambda (λ) is obtained by dividing the sum of values from step 5 by the total number of criterion (4), for example:

$$\text{Lambda }(\lambda) = [4.18 + 4.16 + 4.03 + 4.07]/4 = 4.11$$

where (λ) = 4.11, n = 4; thus $\text{CI} = \frac{4.11-4}{4-1} = 0.04$

$$\text{Consistency Ratio }(\text{CR}) = \frac{\text{CI}}{\text{RI}} \tag{3}$$

Here CI = 0.04, and RI = 0.90 (from **Table 7**); therefore $\text{CR} = \frac{0.04}{0.90} = 0.04.$

Since a CR of 0.04 was obtained from the weights distribution in this analysis, it can be adjudged to be consistent because it is less than 0.9.

5. Modelling PPIR and HCA

The overlay was done with WLC to produce a hazard map indicating distance from the centre of potential source of hazard (oil pipeline), the closer a criterion is to the source (origin) the higher the score given. Land cover and population were considered purely on economic factor; while population was treated the same so that all human population receive equal scores irrespective of size and distribution as in **Table 9**.

5.1. Model Automation

The model builder tools in ArcGIS 10 provide means for automating spatial analysis. The model structure shown in **Figure 4** displayed different tools linked to perform specific tasks [49]; the model can run repeatedly to solve spatial problems [50] [51]. Most GIS models developed in this manner provide visual display of every procedure performed, thereby making it easy to explain, scrutinise, modify, export and reproduce. The tools in the model diagram (**Figure 4**) represents; 1) the orange boxes with one or more input and output, 2) the input (data) variables in blue, and 3) the ovals (green) representing existing data or output, the outputs are products of processes also known as the derived variable. Different colour codes are embedded in the model builder struc-

Table 7. Random inconsistency index table for n = 1, 2, 3, to 15.

N	1	2	3	4	5	6	7	8	9	15
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.59

Table 8. Consistency ratio determination.

Criterion	Stage 4:	Stage 5	
Proximity to pipeline (PP)	$[0.58\times1]+[0.26\times3]+[0.12\times5]+[0.05\times9]=2.41$	2.41/0.58*	4.18
Proximity to river (PR)	$[0.58\times0.333]+[0.26\times1]+[0.12\times3]+[0.05\times5]=1.06$	1.06/0.26	4.16
Land cover (LC)	$[0.58\times0.2]+[0.26\times0.333]+[0.12\times1]+[0.05\times3]=0.47$	0.47/0.12	4.03
Population (P)	$[0.58\times0.111]+[0.26\times0.2]+[0.12\times0.333]+[0.05\times1]=0.21$	0.21/0.05	4.07

*Divide by criterion weight from **Table 6**.

Table 9. Criteria parameter for weighted linear combination and overlay.

Criterion Categorisation	Subhead Scale	Subhead Attribute Weight	Consideration
Proximity to Pipeline (km)			
0.0 - 0.5 0.5 - 1.0 1.0 - 1.5 1.5 - 2.0 2.0 - 2.5 2.5 - 3.0 3.0 - 3.5 3.5 - 4.0	9 8 7 6 5 4 3 1	0.58	Physical Distance
Proximity to River (km)			
0.0 - 0.5 0.5 - 1.0 1.0 - 1.5 1.5 - 2.0 2.0 - 2.5 2.5 - 3.0 3.0 - 3.5 3.5 - 4.0	9 8 7 6 5 4 3 2	0.26	Economic Distance Physical
Land Cover			
Agric-Cultivation Fadama Plantation Minor River Major River Rain-Fed Agriculture Forested Freshwater Swamp Minor Urban Mangrove Forest Major Urban	8 6 3 2 7 6 4 8 4	0.12	Economic Environment
Population Density			
Less-500 501 - 5000 5001 - 15,000 15,001 - 20,000 25,001-over	9 9 9 9 9	0.05	Economic Social Environment

Scale: 9 = Extremely high, 8 = Very very high, 7 = Very high, 6 = Moderately high, 5 = Moderate, 4 = Moderately low, 3 = Very low, 2 = Very very low, 1 = Extremely low.

ture to show the type of tools and steps executed (*i.e.* blue = criteria map layers, yellow = tool, and green = output of a process).

Three outputs were generated in **Figure 4**; the first being the hazard zone classification, the second is the PPIR demarcation and the third is the HCAs designation. The first step creates multiple ring buffers for proximity to rivers and pipelines using equidistance, which was reclassified according to the factors and constraints guideline in **Table 4**. The second stage creates a population point-density layer for the settlements, also reclassified. Finally, an overlay operation was performed with WLC to produce the map shown in depicting different hazard layers base on proximity and intensity. The Potential Pipeline Impact Radius (PPIR) consists of three major hazard layers (zones) define by Equation (4) (**Figure 5**).

$$\text{PPIR} = ehh + vhh + hh \qquad (4)$$

where: *ehh* = extremely high; *vhh* = very high; and *hh* = high hazard zones respectively.

5.2. HCA Designation

All settlements and land features of economic interest within the PPIR buffer (**Figure 6**) are automatically identified as high consequence areas according to illustration (see **Figure 1**). In addition, the presence of a settlement in a HCA is an indication of the presence of human population and the existence of the possibility of pollutant linkages between human inhabitants and oil spill contaminated land use area e.g. land, vegetation and rivers.

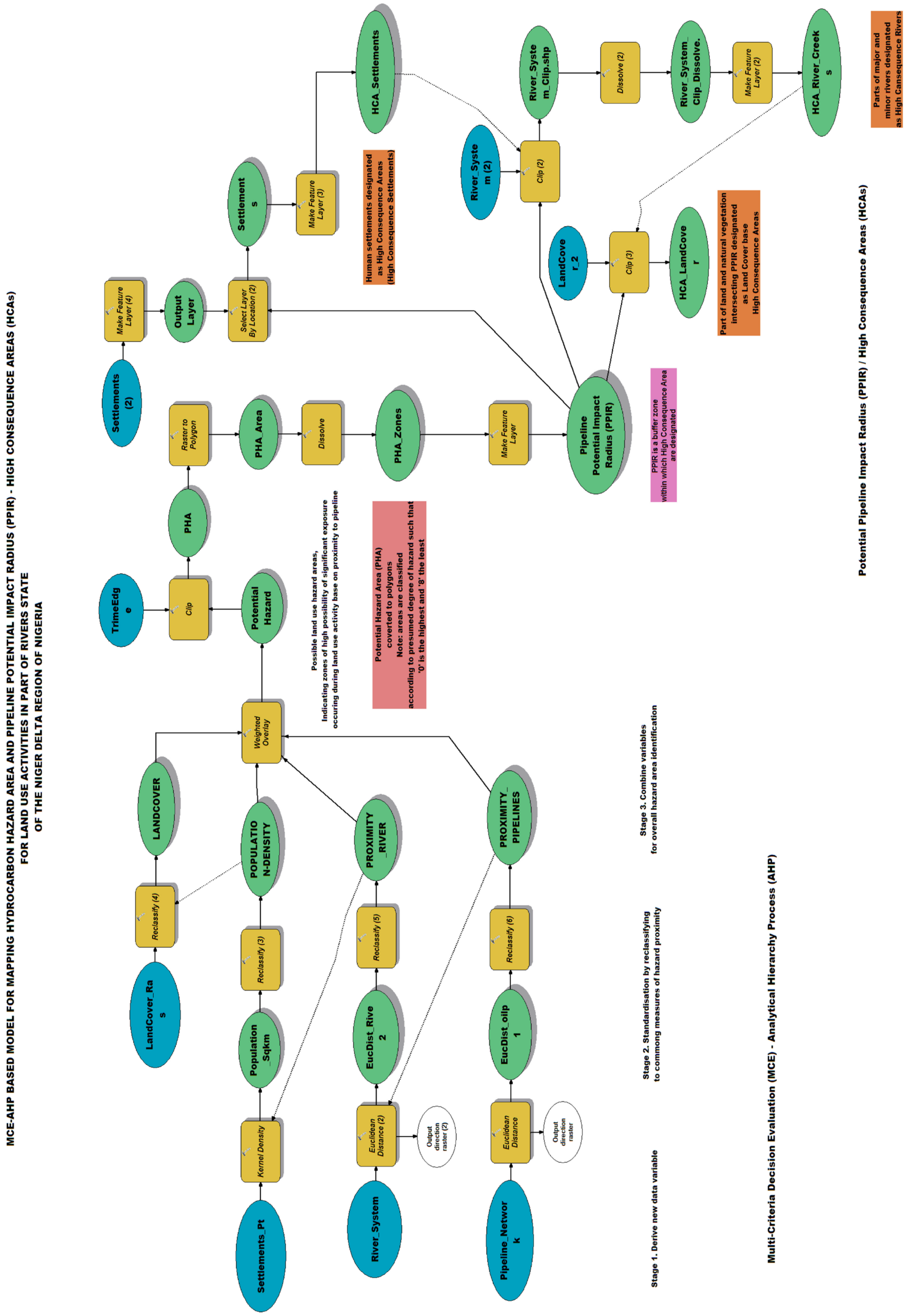


Figure 4. Model structure for the MCDA potential pipeline impact radius and hazard zone modelling.

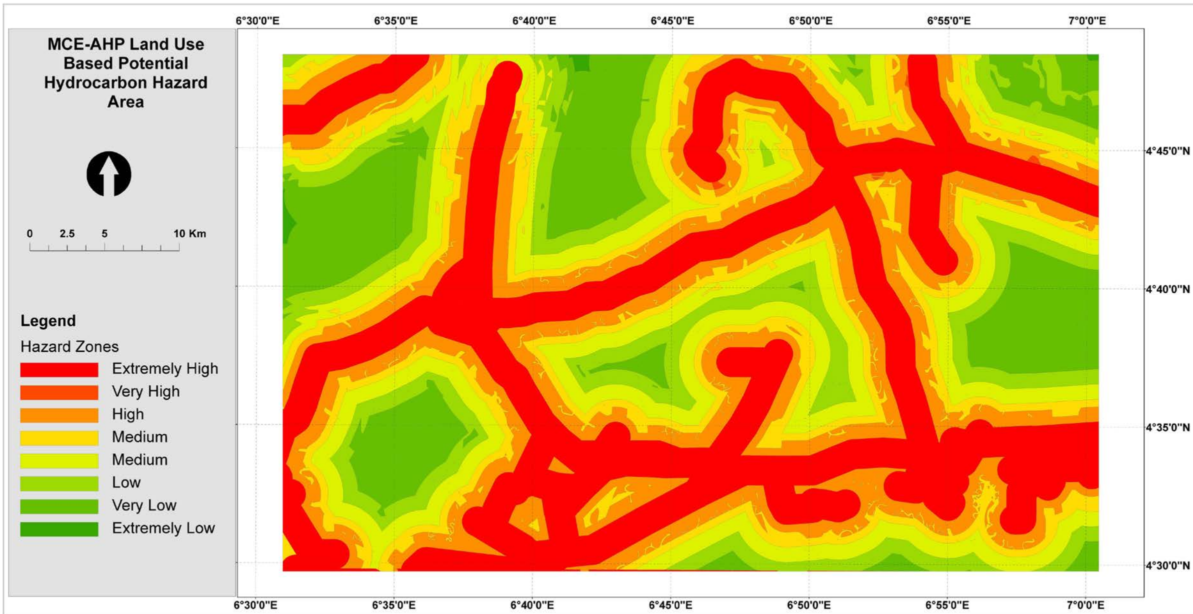


Figure 5. Model of hazard intensity along pipeline routes base on proximity.

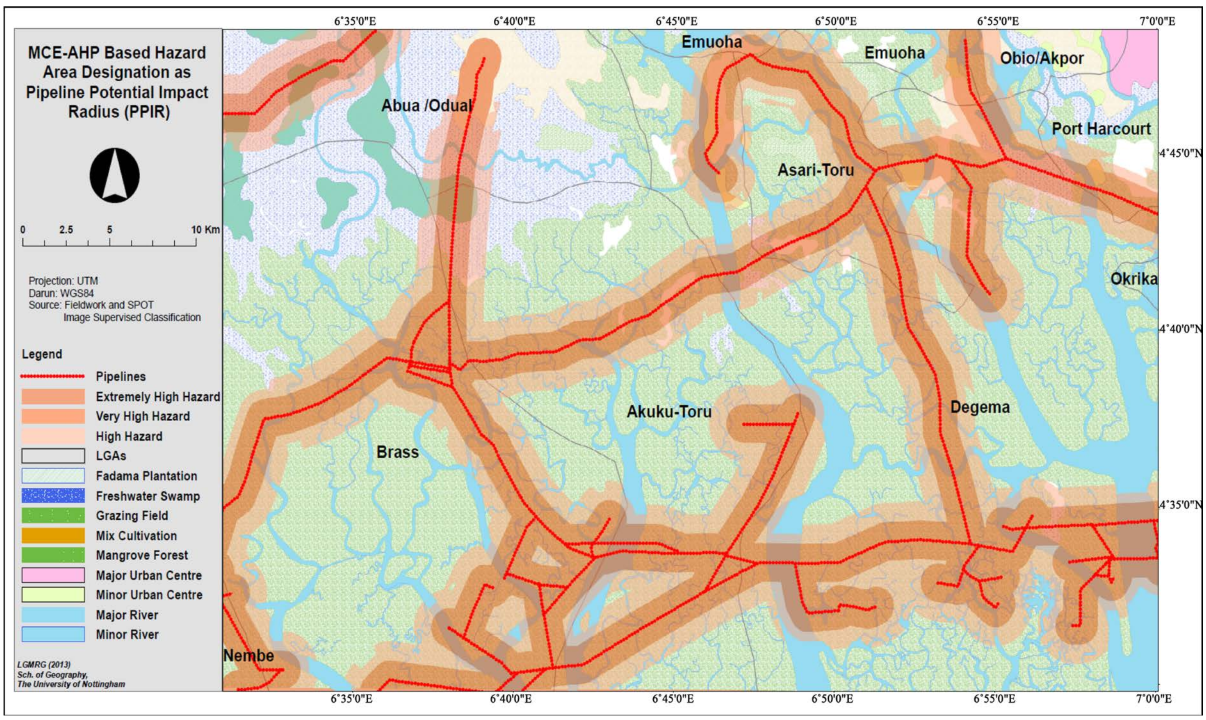


Figure 6. Classification and delineation of PPIR from MCE-AHP hazard zones.

Rivers and creeks surrounding these settlements may serve as pathways to migrating hydrocarbons and point of contact with the people thereby posing significant risk to human health.

In the light of the above, a HCA is an area with potentials to cause risk or damage to properties and exposure to human beings through land use activities e.g. farming, hunting, water consumption etc. However, the intensity of exposure may decrease due to contaminant's loss of concentration with distance from source, while exposure can increase as people come in direct contact with the source point. Hence:

1) properties like farms, fishing grounds etc. that are outside the HCA would not be affected;

2) people working in and living in settlements within the HCA are likely to be the most affected; and
3) people working or living outside the HCA may not be affected.

The percentage (number) of settlements, population, rivers and land cover identified in the HCAs and non-HCAs are shown in **Table 10**.

5.3. Sensitivity Analysis

Sensitivity analysis examines how changes in criterion weight would affect the model, this is important for judging the influence of weight allocation that is based on subjective and or personal preference [52]. If the effect is significant, then the model is said to be sensitive to that particular criterion and consideration is made when handling such criterion in similar operation. The changes can be examined either through visual inspection or statistical comparison. For this model, the weights were systematically redistributed as in **Table 11** for visual comparison in **Figure 7**, which showed no distinctive effect on the primary hazard layers (zones) that constitutes the PPIR in the 1st and 3rd tests. But in the 2nd test where proximity to river was allocated the highest score, this affected the other hazard layers (zones), which is an indication that the model is sensitive to the river network. But since the hazard zones of interest are those define by Equation (4) are not affected, the model can be accepted with reasonable confidence.

6. Discussion

There has been wide-range application of MCDA in different disciplines, e.g. urban and regional planning, nature conservation, natural hazard risk management, and in transportation [16] [25] [35] [53]. The use of GIS for visual representation enables problem solvers to identify pattern, location, direction, and magnitude of a problem for objective decision making purpose. It is these capabilities that this paper exploited to extend the frontier of MCDA application in geo-spatial analysis of oil pipeline hazard/risk to humans and the environment.

Table 10. Characteristics of HCA and Non-HCA area.

Category	HCA (%)	Non-HCA (%)
Settlement	231 (61.9%)	142 (38.1%)
Population	909,519 (69.4%)	401,178 (30.6%)
Est. No. of Household[3]	113,689.9	50,147.2
Male	410,464.2	181,052.1
Female	499,054.8	220,125.9
Under 14 years	333,496.2	147,231.7
River (sq.km)	134,470.9 (39.2%)	208,680.3 (60.8%)
Major	101,099.3 (sq.km)	162,621.5 (sq.km)
Minor (Creeks)	33,371.6 (sq.km)	46,058.8 (sq.km)
Land Cover (sq.km)	765,275.5 (39.9%)	1,154,097.9 (60.1%)
Fadama Plantation	16,417.9 (sq.km)	26,592.7 (sq.km)
Freshwater Swamp	63,037.7 (sq.km)	147,929.6 (sq.km)
Grazing Field	9734.9 (sq.km)	9506.3 (sq.km)
Mangrove Forest	628,752.7 (sq.km)	565,756.4 (sq.km)
Mixed-Cultivation	27,646.3 (sq.km)	35,014.5 (sq.km)
Others	19,686 (sq.km)	369,298.4 (sq.km)

Table 11. Sensitivity analysis by weights redistribution.

S No.	Criterion	Weight in Percentage (%)			
		Original	1st Test	2nd Test	3rd Test
1	Land Cover	12	58	26	5
2	Population Density	5	26	12	58
3	Proximity to River	26	5	58	12
4	Proximity to Pipeline	58	12	5	26

[3]The state average household is eight family members based on the 2006 Census (NPC, 2012). This was adopted to estimate the number of households.

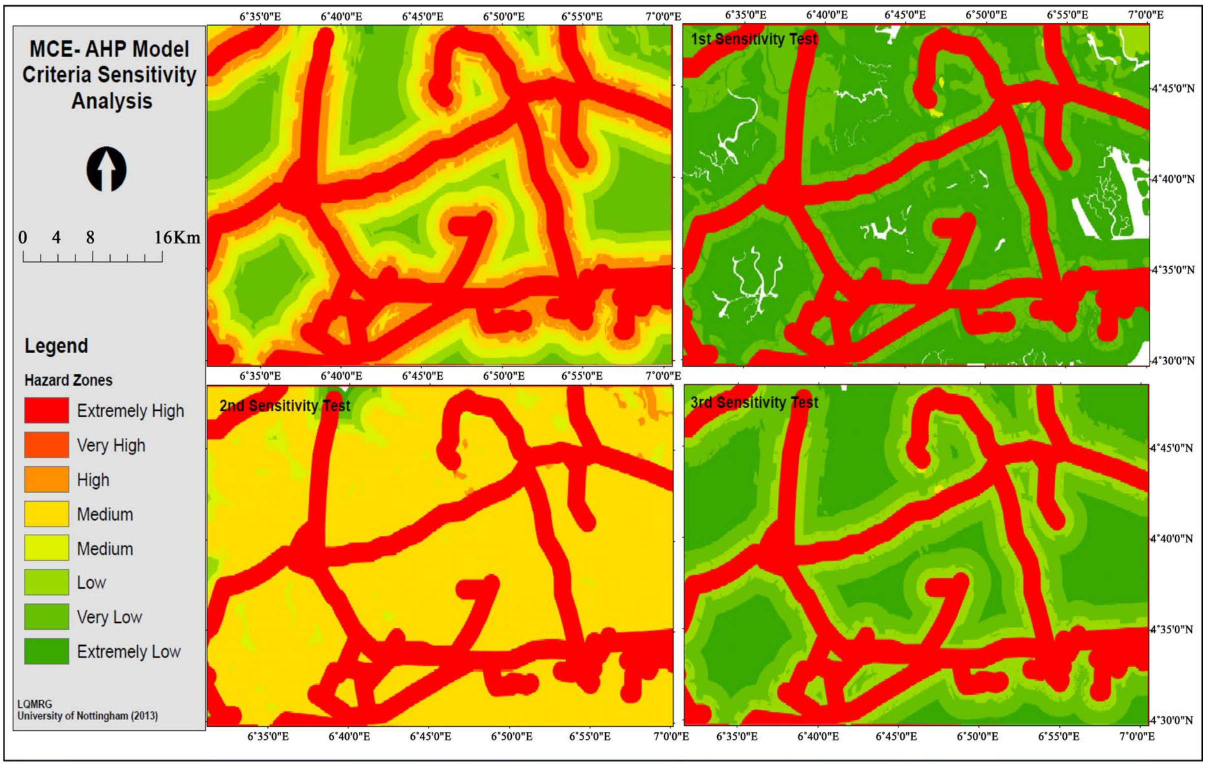


Figure 7. MCDA-AHP model sensitivity test by weight redistribution.

From literature, the original PIR demarcation is dependent on pipeline parameters that are not easily available in the public domain in Nigeria for security reasons, according to the oil companies. The model developed herein provides a new approach using easily available data and expert knowledge that can be acquired in the public domain to provide means of public participation in pipeline hazard management in the area. The method (MCDA) established the PPIR from the interaction of social, economic and physical attributes to identify land use areas, river systems and communities likely to be affected directly or indirectly by oil pipeline spill hazard. These areas represent places where pipeline failure is likely to cause significant adverse impact on human population, source of domestic water, and ecologically sensitive receptors. [54] reported wide-spread concentration of total petroleum hydrocarbon (TPH) in samples collected several meters away from discharge points. This explains the ease with which petroleum hydrocarbons migrate in the Niger Delta wetland environment. Thus the minimum 1 km requirement for hydro-census investigation of suspected contaminated sites in South Africa [55], and the 500 - 2500 meters primary and secondary pipeline impact buffer hypothesised by [56] gave credence to the 1 km buffer generated by the MCDA-AHP model.

From the weights derivation, proximity to pipeline has the highest score of 0.58, proximity to river 0.26, land cover 0.12, and population 0.05. It is obvious that proximity to pipeline is a very significant (important) criterion being the main source of hydrocarbon discharge in the area. Proximity to river was second; considering the behaviour of crude oil on water and the land being a wetland area. The rise and fall of water levels due to seasonal inundation can promote easy migration of free and trapped hydrocarbons into adjacent water bodies and land use areas through vertical spreading and surface run-off [54] [57]. Land cover on the other hand can retard free movement of crude oil on ground surfaces and at the same time promote vertical and horizontal migration of hydrocarbons through the soil vadose zone. Last but not the least is population density, which was calculated per square kilometer (km^2) and used to determine population concentration and existence of human settlements in the hazard zones (PPIR). Consequently about 62% of the 374 settlements in the study area were found within the HCAs with no fewer than 69% of the 1.3 million people living in susceptible communities. The main factor for designating HCAs is the existence of human habitats within the predefined analysis area indicated by the MCDA-AHP hazard zones, showing general decrease in hazard intensity with increase in distance from source (pipeline) in obedience with the theory of chemical diffusion. The direct HCAs represent areas that are within the immediate vicinity of a pipeline segment that may suffer direst impact, while the indirect HCAs are areas only impacted by migrating hydrocarbons through specific pathways.

The HCAs in the context of land use are settlements from where human movement originates, river and creek networks that serve as fishing ground, source of domestic water and abstraction points, and land cover on which farming, hunting, and wild gathering is conducted **Table 10** shows the characteristics of the HCAs and non-HCAs; the non-HCAs are areas outside the PPIR corridor that are considered to have better chance of surviving oil spill hazards. The HCA designator generate tables with information on settlements in that HCAs, the data can be used to determine population distribution and household characteristics of a given risk area for compensation and or mitigation purposes. The model not only provide easy tool for examining high consequence communities (HCC) by their specific characteristics, it can also be updated regularly for monitoring purpose. This model provides visual display and detailed procedures of steps executed for easy explanation, independent scrutiny and verification, modification for improvement, export for other use and reproduction.

7. Conclusions

An automated tool that can be used to monitor human (settlement) susceptibility to pipeline hazards in wetland areas has been developed for public participation and collaboration in pipeline hazard management and

- Help decision makers since the platform (model) has the ability to maintain itself and update existing database of HCAs each time it is run. This would provide updated information on population growth and land use expansion relative to pipeline network.
- The information generated from desktop assessment would improve collaboration with new communities that just qualified as HCAs, thereby reducing operational cost and facilitate direct community base participation in the fight against oil pollution and pipeline interdiction in the area.
- The regular updating of high consequence communities as new ones emerge would help in equitable distribution of response facilities and resources for mitigating risk of prolong exposure to impact of pipeline hazards.
- The identification of land use areas in HCAs can provide useful information for land use planners and policy makers in the oil and gas sector as well as provide impetus for driving environmental sustainability in oil production activities in the region.
- It is also recommended that responsible government agencies like the National Oil Spill Detection and Response Agency (NOSDRA), the Department of Petroleum Resources (DPR) and the Nigerian National Petroleum Corporation (NNPC) and the Federal/State Ministry of Environment to be equipped with the capabilities (employing experts and technology) to deploy this technology/technique in pipeline hazard risk management and assessment in the oil producing areas of Nigeria.

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