

Natural Habitat vulnerability modeling critical to Contingency planning for areas susceptible to potential spill impact from crude oil facilities in Niger Delta Nigeria

Abstract

Oil spill vulnerability to natural habitats was performed using the ArcGIS 10.3.1 and its Spatial analyst extension. The input variables were land use land cover imagery, pipelines, wellheads and a flow station. Oil spill was modeled as a function of spread through land uses. Impedance function was applied to oil spill spread through the landscape for oil well, pipeline and flow station. Total function risk was modeled as the iteration of aggregate oil facility cost surface (likelihood) and environmental sensitivity cost surface (consequence). Three classes generated were high, medium and low vulnerability surfaces. The surfaces were used to extract landuse and landcover susceptible to any potential spill impact from three scenarios generated within three buffer zones of 50meter, 100m and 150 meter using GIS overlay techniques. Each vulnerability surface within the defined buffers was able to quantify pixels of landuse and landcover types susceptible to the risk of a potential oil spill. When utilized correctly using an appropriate scale and spatial resolution, raster-pixel based vulnerability surfaces have the potential to be effective tools in Contingency planning for appropriate response.

Keywords: Natural Habitats, Landuse, Landcover, Vulnerability, GIS

1.0 Introduction

Nigeria is one of the major oil producers in Africa with a history of inland and coastal spill history. Documented evidence shows that between 1976 and 2001 a total of 6744 incidents of oil spill in both coastal and inland the environment [1] occurred. The complex interactions between the time of spill and the consequences to biological systems require applications that can iterate multicriteria variables for better understanding of response efforts. In Nigeria today oil spill response is provided by a number of strategies which includes the use of dispersants, oil skims, booms and shoreline clean up assessment surveys (SCAT). The rate of response is therefore dependent on the integration of information about the size of the spill, direction and potential human and natural resources at risk. Oil spill Vulnerability modeling can therefore be used to enhance the level of preparedness by pre-identification of

the vulnerability of natural resources at risk. This can be integrated with shoreline/ habitat types to develop site specific response strategies modeled at different scenarios. This approach to contingency planning has been documented in a number of studies [2-9]. To address this kind of integrated planning Geographic Information System and Satellite Imagery were used to model potential risk from oil spill to natural resources within a land based area in southern Nigeria.

2.0 Study Area

The study area (Fig 1.0) is sandwiched between the Sombriero River and Orashi River drainage basins and is within the geographic coordinates of $6^{\circ}36'11.13''E$, $5^{\circ}16'23.749''N$ and $6^{\circ}41'18.854''E$, $5^{\circ}12'4.574''N$. The Area of Interest (AOI) cover a total of 10,899.99 hectares containing different landuse and landcover classes which includes six major communities belonging to the Egi clan. The habitat classes consist of swamp forest, agricultural land and grassland ecosystems containing a diversity of biologically sensitive groups. Within this study sites are peculiar floodplain ponds within depressions located along the rivers and creeks which serve as important fisheries to the communities. The major oil infrastructure extracted from satellite imagery (Landsat TM imagery 2013) includes; a petroleum central flow station, gas and oil pipes and well heads.

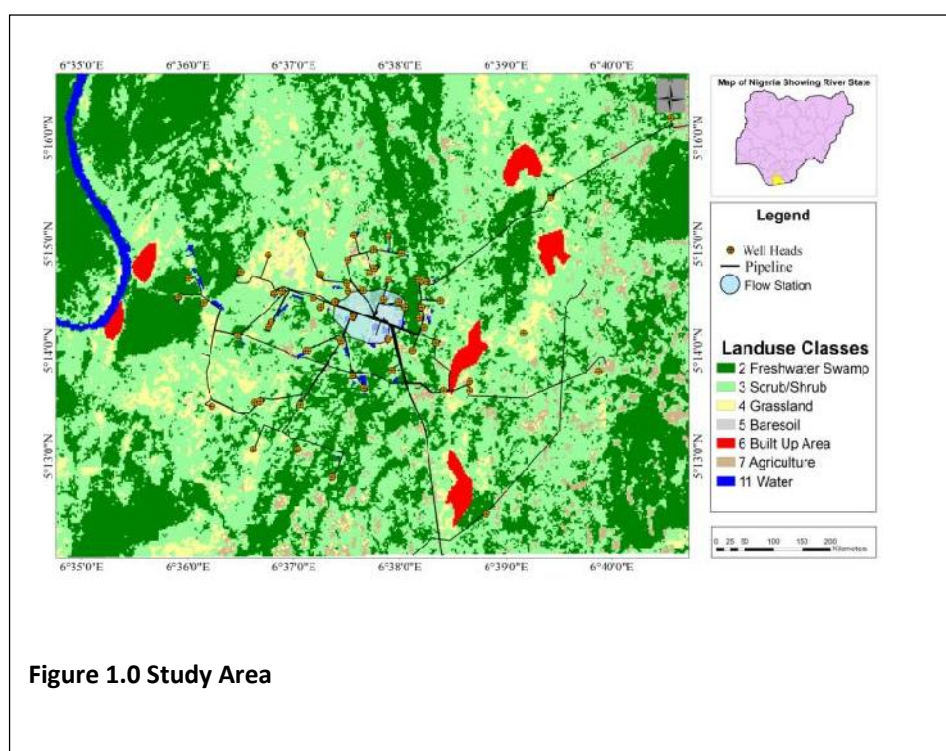


Figure 1.0 Study Area

3.0 Materials and Methods

Satellite imagery from Landsat 7 ETM of 2013 was processed and post processed after groundtruthing with ERDAS Imagine into Landuse and Landcover classes as shown in Fig. 1.0. The Landuse and landcover classes were input into ESRI's ArcGIS 10.3.1 which was the primary software used for all the analysis. Modeling was implemented through the optimal utilization of different tools and modules of Spatial Analyst Extension in the ArcGIS 10.3.1 environment for cartography, modeling and spatial query.

Three sources of potential oil spill namely well heads, flow station facility and pipelines were identified and used as input datasets in addition to the Landuse/Landcover (LULC) of the study area. The study identified the maximum relative risk for each criterion and aggregated them. To this effect the cost of oil migration from each criterion (well heads, flow station, and pipelines) was identified by employing a Euclidean distance tool which develops a straight-line distance from each input feature cell such as wells, oil facility or pipeline to the closest source of objects of interest such as landuse and landcover.

In order to iterate the nonlinear migration pattern of oil spills, an oil migration impedance surface was generated which provides the cost of migration by generating a friction/cost surface or impedance surface. A scale of 1-7 was used to classify the cost to the oil as it migrates through the landuse-landcover features. Impedance costs were assigned with 1= low impedance and 7= Very high impedance. Table 1.0 shows the values which were used as the input cost grid or cost values for each landuse and landcover (LULC) features:

Table 1.0 Input cost grid value for LULC feature

Landuse-Landcover	Impedance Class	Impedance Category
Water	1	low
Bare Soil	2	low
Grass	3	moderate
Agricultural Land	4	moderate
Regrowth Vegetation	5	high
Freshwater Swamp	4	moderate
Built-Up Area	7	Very high

A cost surface was developed by using as input the classification of impedance values of land cover and planimetry information. The cost distance surface was developed by

identifying for each cell the weighted accumulative cost of transport of oil across the landscape from the nearest potential source of oil spill. A cost distance surface was developed by reclassifying the Euclidean distance surface from each input facility into a proximity surface on a scale of 1-10 with nearest cells at greater vulnerability. Similarly the cost surface was reclassified on a scale of 1-10 with higher cost for cells that are at closer proximity of the source location dataset. A Cost distance surface was developed by iterating the Euclidean distance surface and the cost surface raster. Figures 5.0, 6.0 and 7.0 below illustrate the derived cost distance surfaces for flow station, pipeline and wellhead respectively. The highest risk areas are shown in yellow, while lowest risk areas are shown purple. An aggregation of risk was performed by merging the and minimum and maximum cost of oil transport across each surface into a single layer in order to develop a risk maximizing effect with the greatest exposure to oil spill risk across all risk sources. Cost is weighted by source type; pipelines and flow station represent the greater portion of risk, while wellhead is a lower risk factor. The result is a synthesis of all sources of oil spill risk to a single surface. A consequence cost surface was developed from the environmental sensitivity values of the habitats within the area of interest. The source input values were derived from the ESI (NOAA 2002) classification scheme of the habitats within the AOI. The Environmental Sensitivity Index (ESI) is a weighted landscape sensitivity surface based on land cover, land use and planimetry. For example, areas that are extremely sensitive to oil spills, such as freshwater swamp forests, receive high sensitivity scores. Areas of higher resistance to oil spills, or areas that already have been affected by significant human use receive lower sensitivity scores. Table 2.0 below shows the sensitivity values assigned to the LULC classes for the generation of the sensitivity surface.

Table 2.0 Environmental Sensitivity Index classes

Landuse-Landcover	Sensitivity Values	Sensitivity
Water	1	Low
Grass/ Baresoil	4	Low
Built-Up Area	5	moderate
Agricultural Land	6	moderate
Regrowth Vegetation	7	High
Freshwater Swamp	10	High

Vulnerability was modeled as the iteration of aggregate risk surface and the consequence cost surface. Vulnerability (Risk) was expressed as in the following formula:

Vulnerability = Aggregate Risk (likelihood) x Consequence (Habitat Sensitivity).

4.0 Results

Figures 2.0, 3.0 and 4.0 present the Euclidean distance surfaces for the source data sets of facility, pipeline and wellheads. The proximity surfaces provide visual measurements of concentric equidistance zones established around the source data sets of the facility (Fig 2.0), pipelines (Fig 3.0) and wellheads (Fig 4.0). Each ring indicates raster cells composed of Euclidean increasing distance from the potential oil spill source dataset with darker colors representing increasing distance. Proximity was measured as a series of propagating rings of raster cells emanating from the source data sets with the distance zones reflecting the type of potential oil spill movement. In these cases, the effective proximity resulted in the same equidistance.

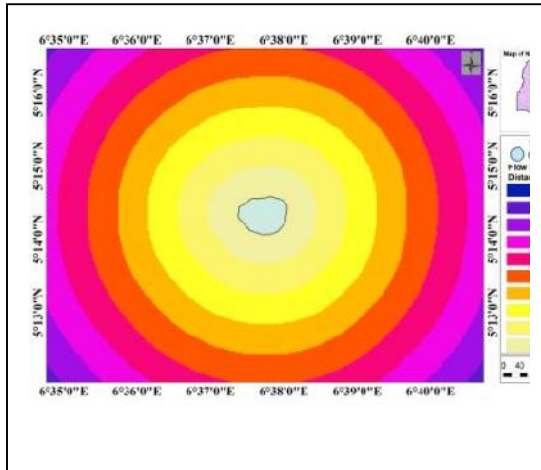


Fig 2.0. Reclassified Euclidean distance risk surface of potential oil spill from flow station

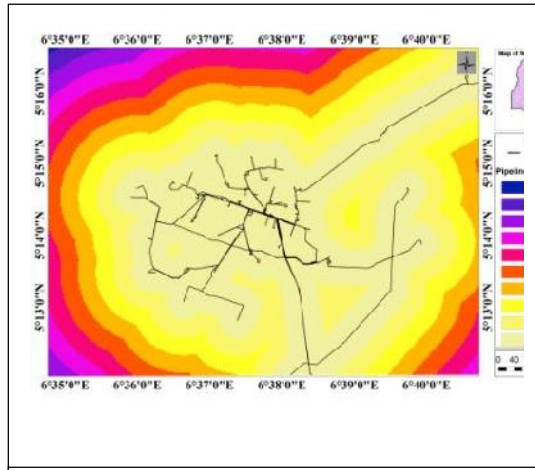


Fig 3.0. Reclassified Euclidean distance risk surface of potential oil spill from Pipelines

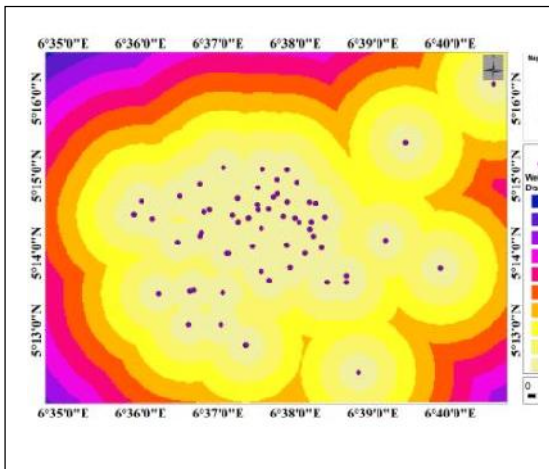
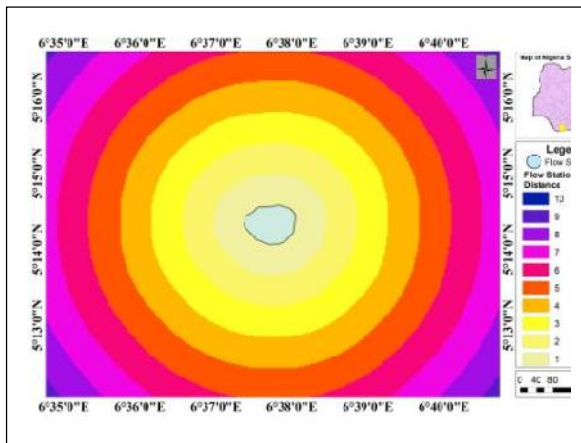


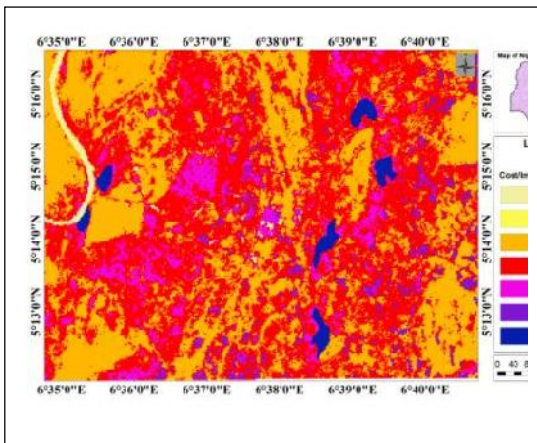
Fig 4.0. Reclassified Euclidean distance risk surface of potential oil spill from oil wells

In Figs 5.0, 6.0 and 7.0 are shown the results of incorporating relative barriers to the potential Euclidean movement of potential spilled oil. By encoding into the Euclidean distance surface, relative barriers of planimetric data, figures 5.0, 6.0 and 7.0 illustrate the results of cost distance iteration in propagating potential spilled oil and in determining effective proximity. As the potential oil spill encounters the diverse planimetric barriers, their effects on movement are incorporated and distort the symmetric pattern of simple Euclidean proximity movement. The results of effective proximity are shown in figs 8.0, 9.0 and 10.0 with the concentric rings of raster cells warped with bumps and ridges that reflect the intervening conditions with greater impedance producing more concentric distortions.

The composite potential oil spill migration risk surface is shown in Fig 11.0. This represents the composite cost surface whose values are the spatially coincidental migration cost of each data source (facility, pipeline and wellheads) thematic characteristics. Figure 11 is represented using a color ramp to show the transition of ease or difficulty of migration pattern of potential spilled oil. The vulnerability surface of the Area of Interest (AOI) is shown in fig 14 and represents the iteration of the composite oil spill migration surface and the consequence cost surface. Vulnerability are shown in three classes of color with the highest in deep tones of blue followed by moderate areas in tones of red and low areas in tones of light yellow.



Euclidean distance surface



Cost Surface raster

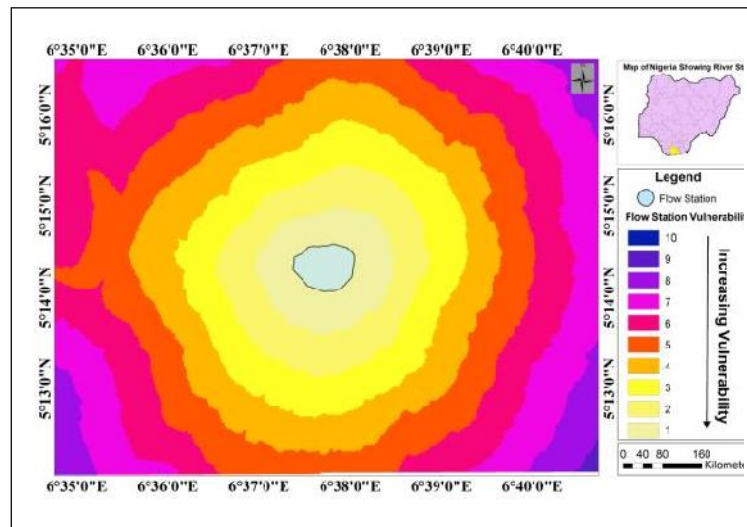
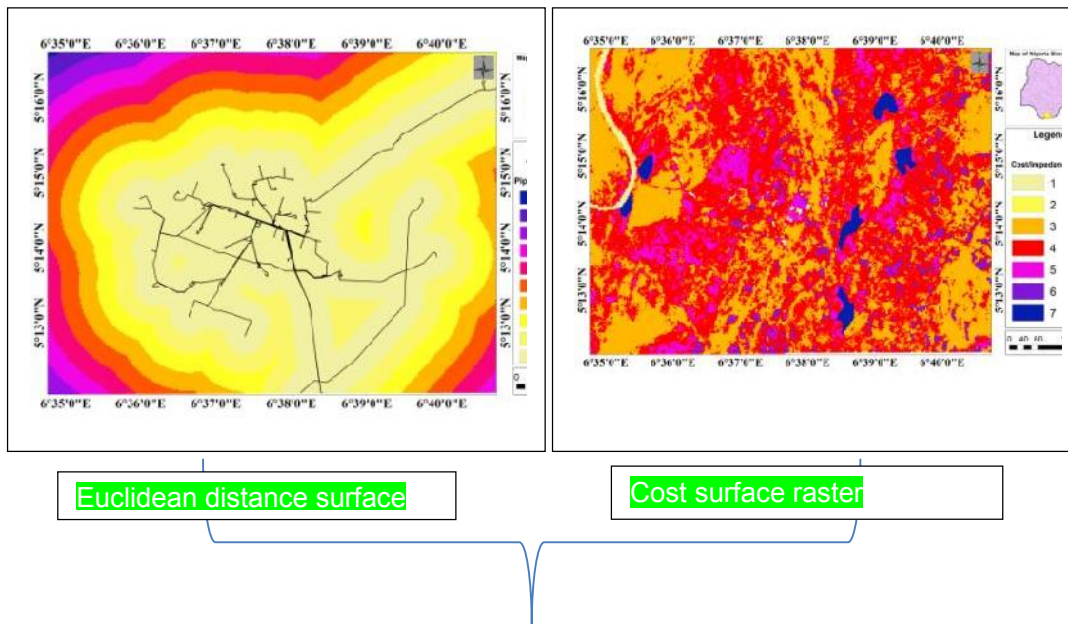


Fig 5.0. Cost distance surface for potential oil spill migration from Flow Station



Euclidean distance surface

Cost surface raster

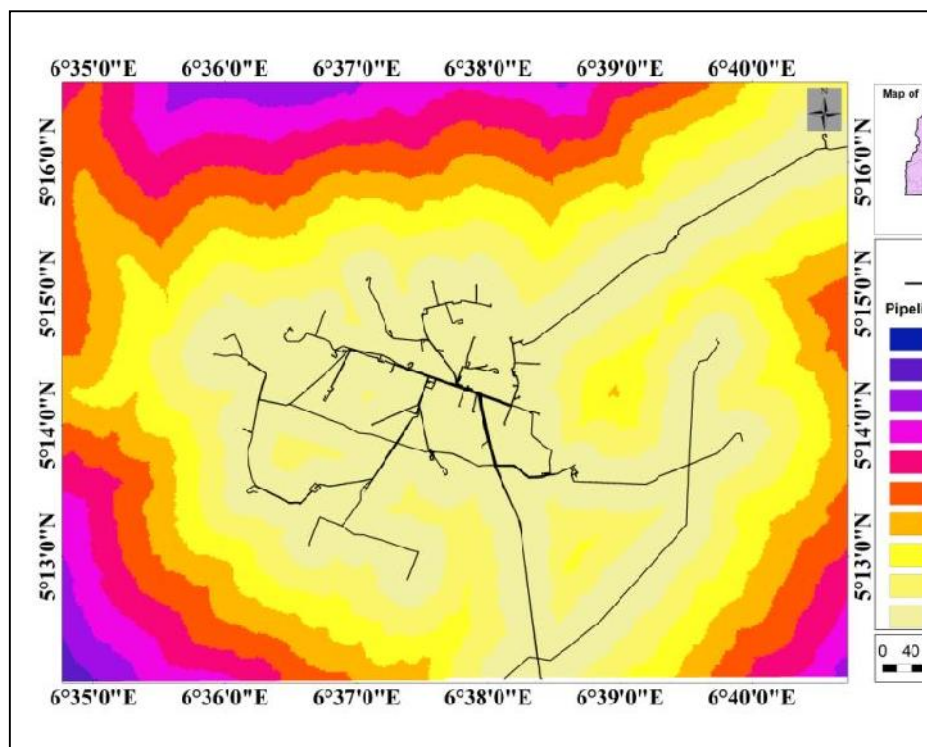
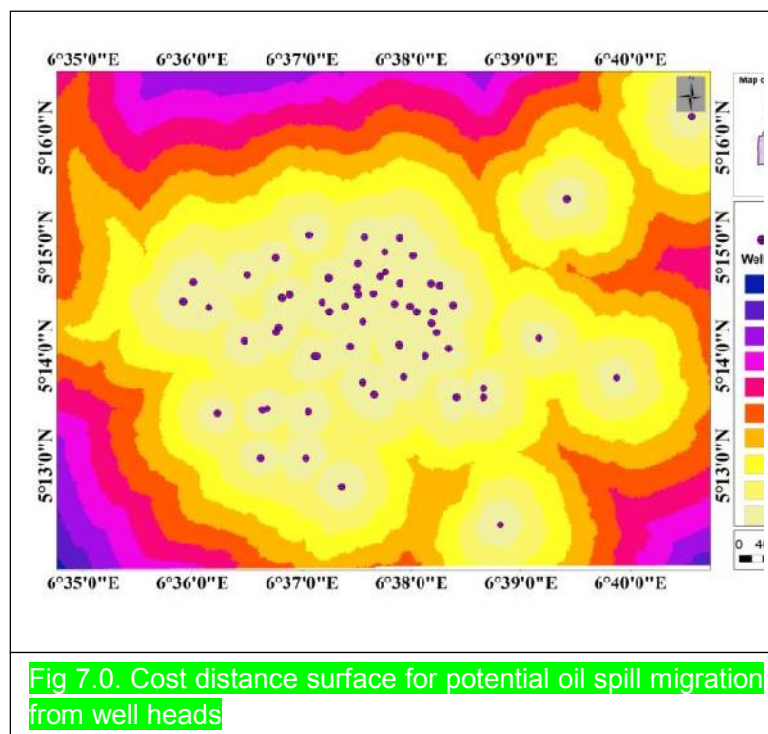
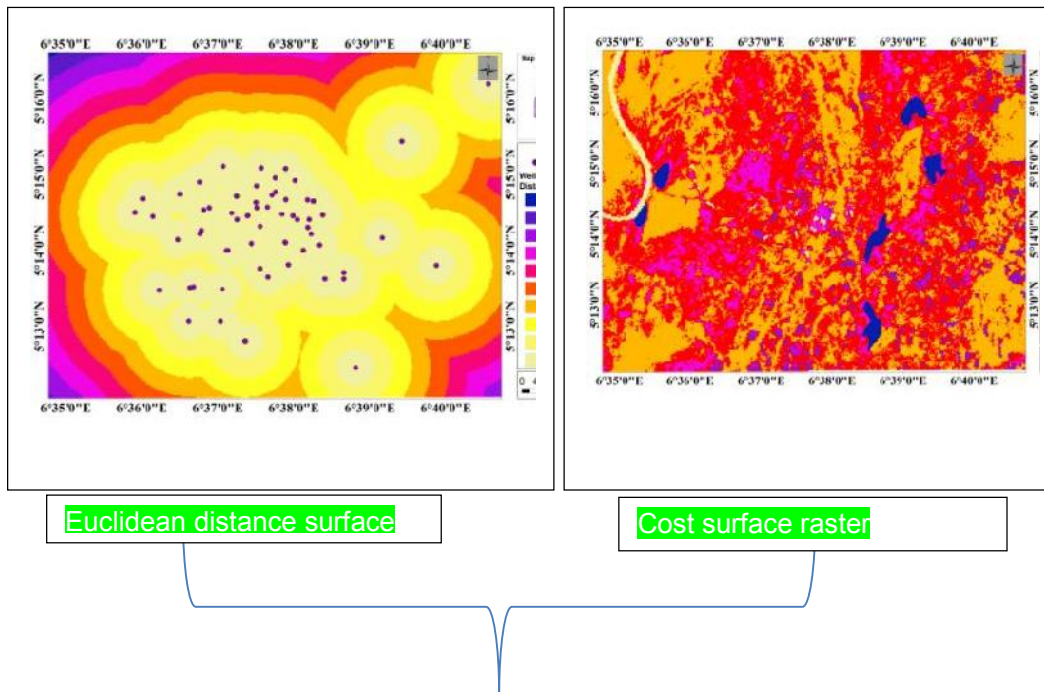


Fig 6.0. Cost Distance surface for potential oil spill migration from pipeline



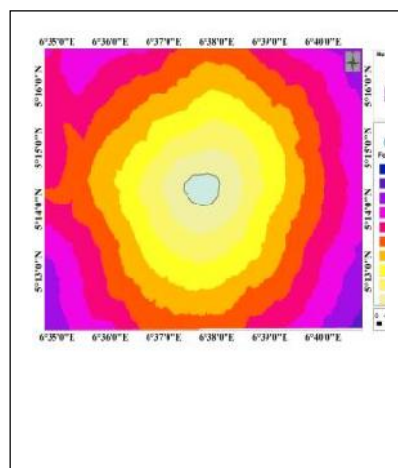


Fig 8.0. Cost distance surface-flowstation

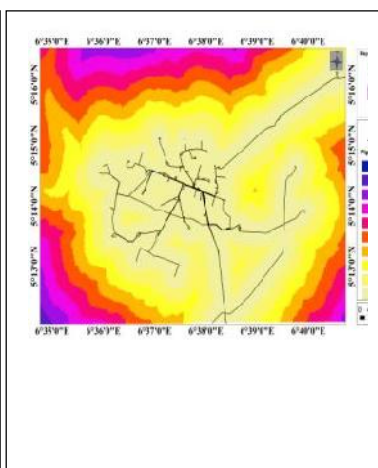


Fig 9.0. Cost distance surface-pipeline

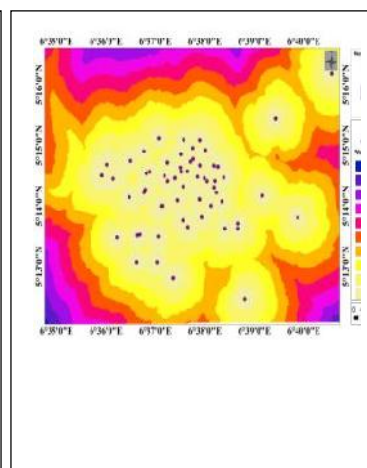


Fig 10.0. Cost distance surface-oil well

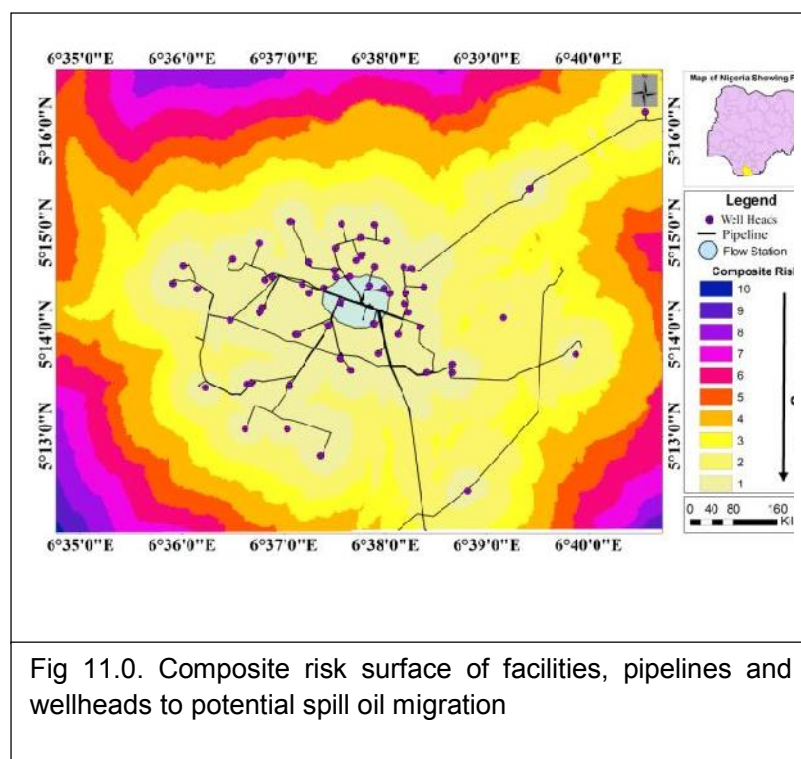


Fig 11.0. Composite risk surface of facilities, pipelines and wellheads to potential spill oil migration

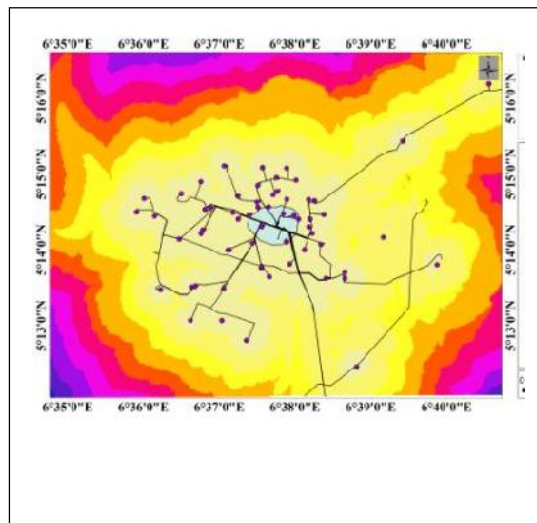


Fig 12.0. Composite risk surface
(flowstation, pipeline, wellhead)

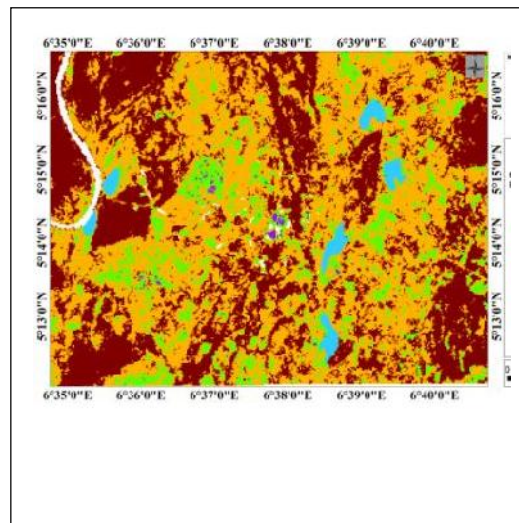


Fig 13.0. Consequence surface

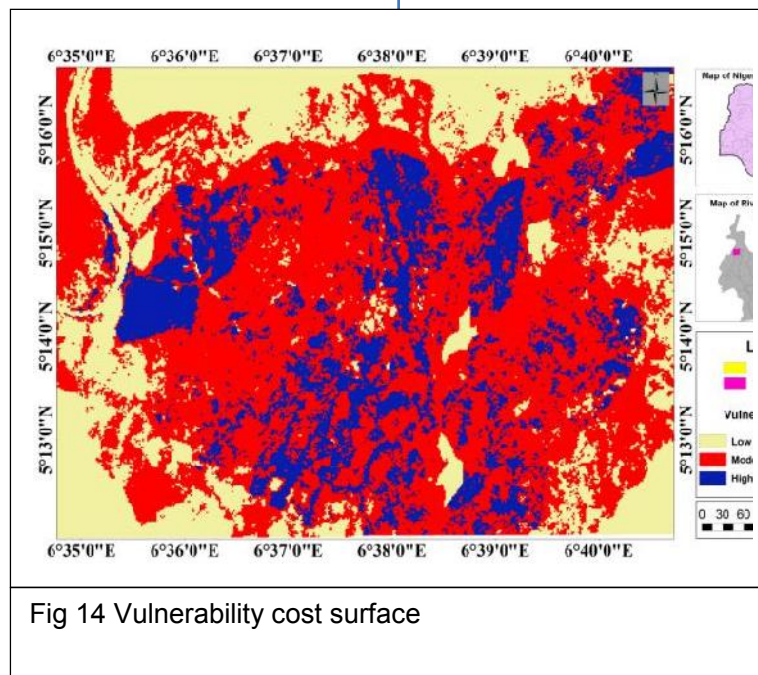


Fig 14 Vulnerability cost surface

4.1 Habitat Vulnerability Surface Analysis

Figs 15.0, 16.0 and 17.0 show the vulnerable areas of habitat with potential exposure to the composite facility (flow station, pipeline, wellheads) vulnerability model surface. In Fig 22.0 the model shows that the surface area of the high vulnerability that would be exposed to a potential spill in a 50m, 100m and 150 m meter buffer zones would be 131 hectares, 268 hectares and 409 hectares respectively. This was spatially coincident in an overlay process to the landuse landcover habitats that belonged only to the freshwater swamp forest as shown in figs 19.0, 20.0 and 21.0.

Fig 18.0 is shown the surface area of medium vulnerability surface that would be exposed to a potential oil spill in a 50m, 100m and 150 m meter buffer zones from the composite facility (flow station, pipeline, wellheads) as 502 hectares, 849 hectares and 1147 hectares respectively. These were spatially coincident in an overlay process to four landuse landcover habitats which were namely Freshwater Swamp, Regrowth Vegetation, Grass/Scrub and Agriculture as shown in Figs 23.0, 24.0 and 25.0.

In fig 18.0 is shown the area of low vulnerability surface that would be exposed to a potential oil spill in a 50m, 100m and 150 m meter buffer zones from the composite facility (flow station, pipeline, wellheads) as 50.13 hectares, 78.57 hectares and 106.55 hectares respectively. These were spatially coincident in an overlay process to five landuse landcover habitats which were namely Freshwater Swamp, Regrowth Vegetation, Grass/Scrub, Agriculture and water as shown in Figs 27.0, 28.0 and 29.0.

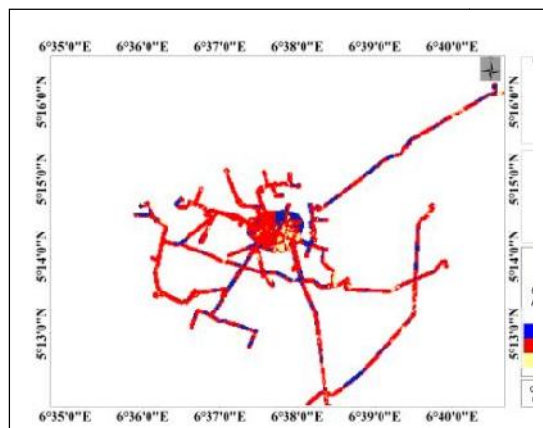


Fig 15 Exposed surface area of Vulnerability Classes within a 50 m buffer zone

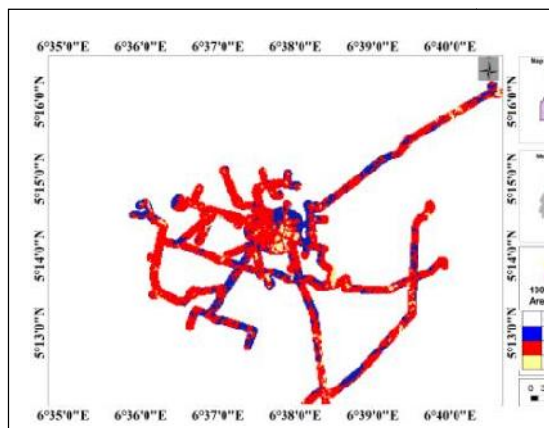


Fig 16 Exposed surface area of Vulnerability Classes within a 100 m buffer zone

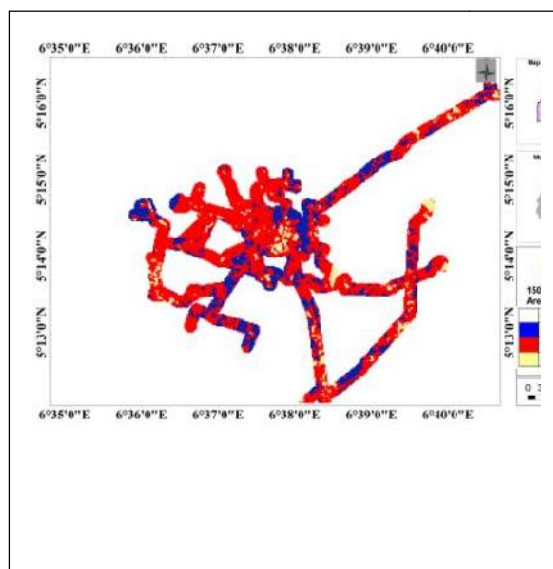


Fig 17 Exposed surface area of Vulnerability Classes within a 150 m buffer zone

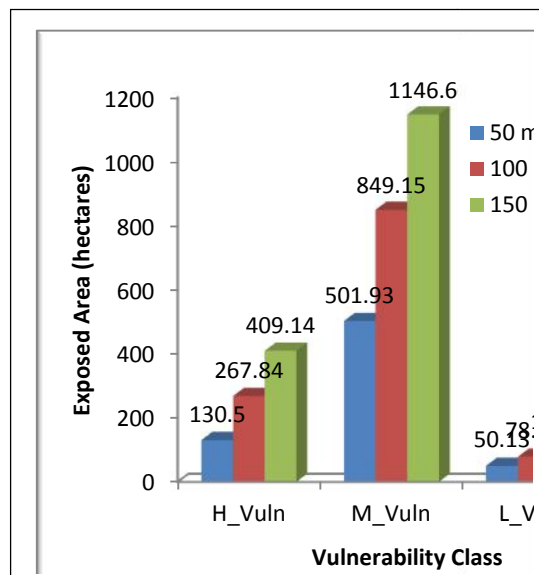


Fig 18 Quantified surface area of Vulnerability Classes exposed within 50m, 100 m and 150 m buffer zones

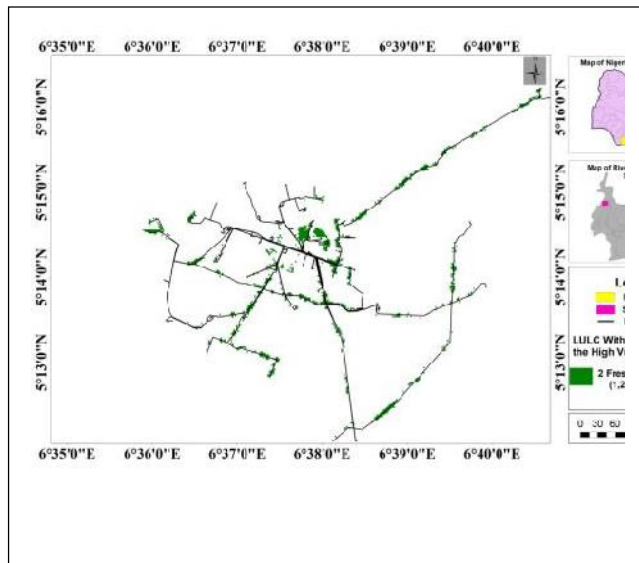


Fig 19.0. Susceptible habitats at risk within high vulnerability surface (50 meter scenario)

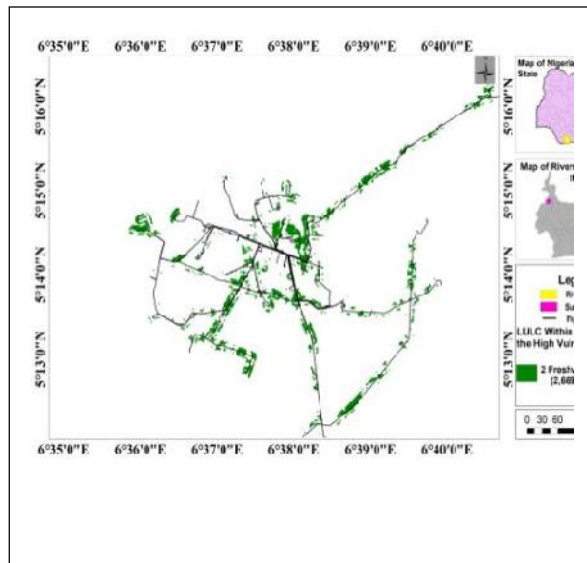


Fig 20.0. Susceptible habitats at risk within high vulnerability surface(100 meter scenario)

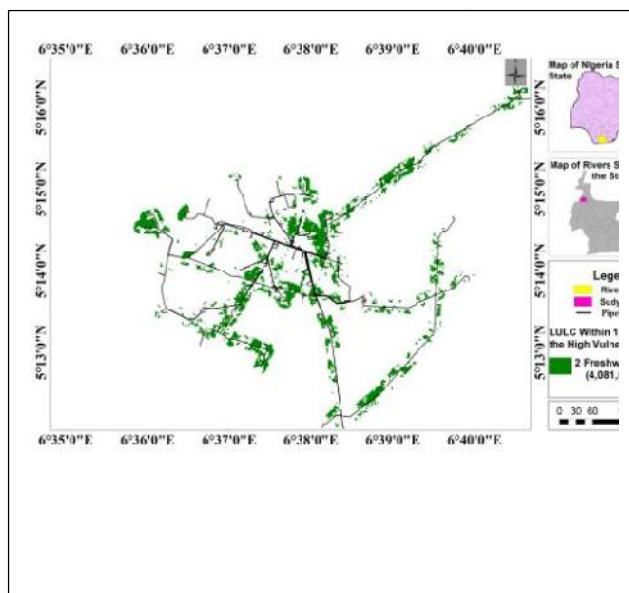


Fig 21.0. Susceptible habitats at risk within high vulnerability surface(150 meter scenario)

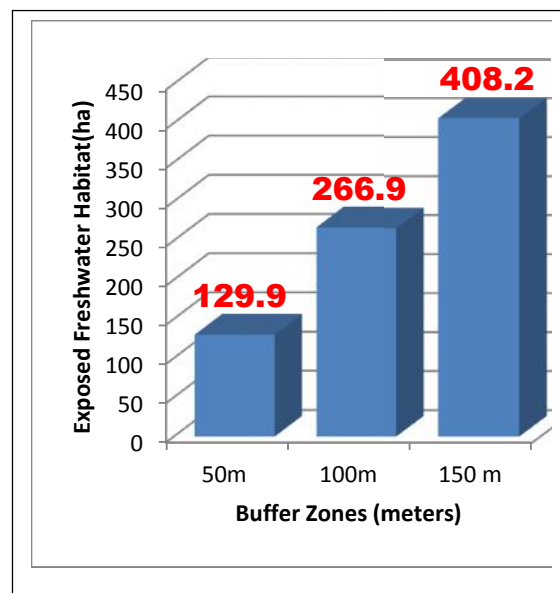


Fig 22.0. Area(ha) of Susceptible habitats at risk within high vulnerability surface(50, 100 and 150 meter scenarios)

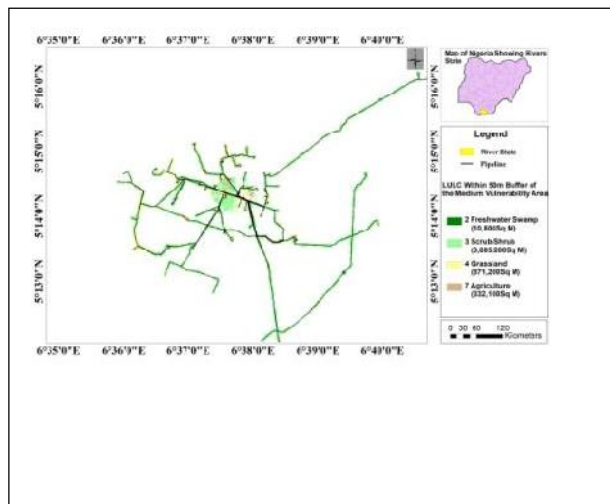


Fig 23.0. Susceptible habitats at risk within medium vulnerability surface (50 meter scenario)

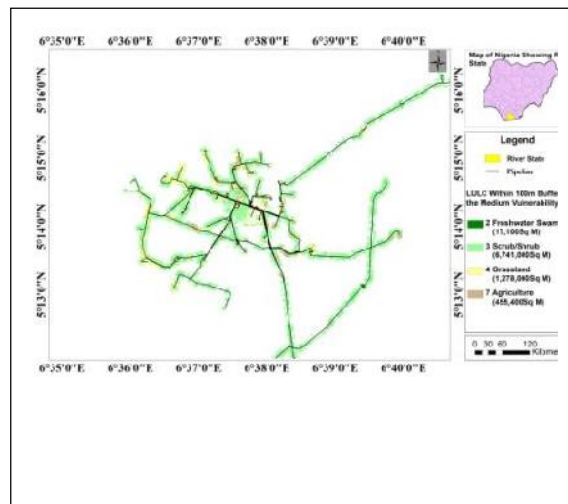


Fig 24.0. Susceptible habitats at risk within medium vulnerability surface (100 meter scenario)

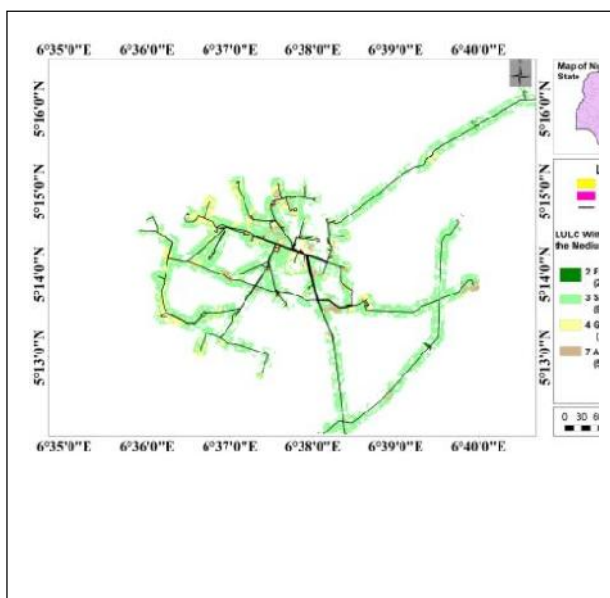


Fig 25.0. Susceptible habitats at risk within medium vulnerability surface (150 meter scenario)

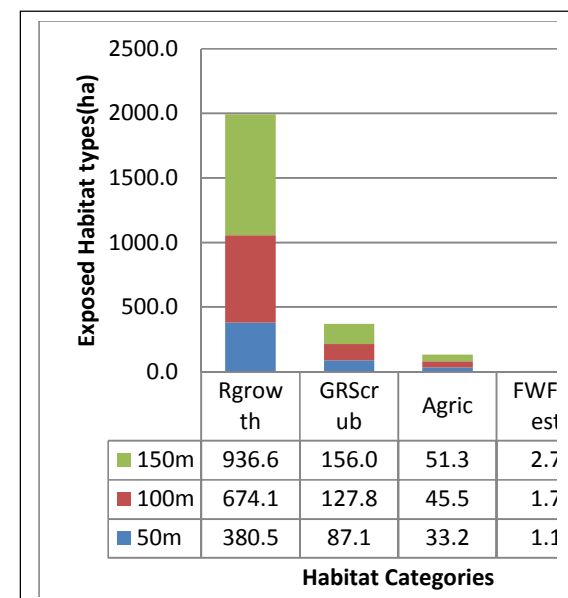


Fig 26.0. Area (ha) of Susceptible habitats at risk within medium vulnerability surface (50, 100 and 150 meter scenarios)

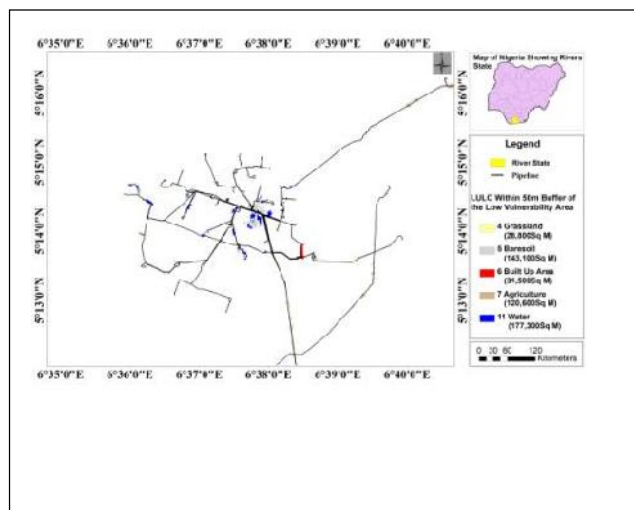


Fig 27.0. Susceptible habitats at risk within low vulnerability surface (50 meter scenario)

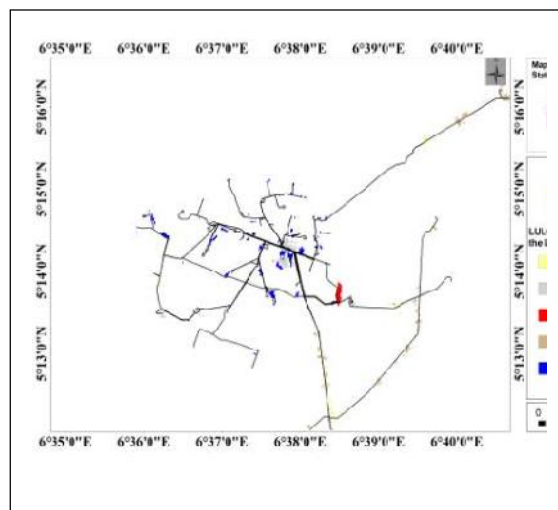


Fig 28.0. Susceptible habitats at risk within low vulnerability surface (100 meter scenario)

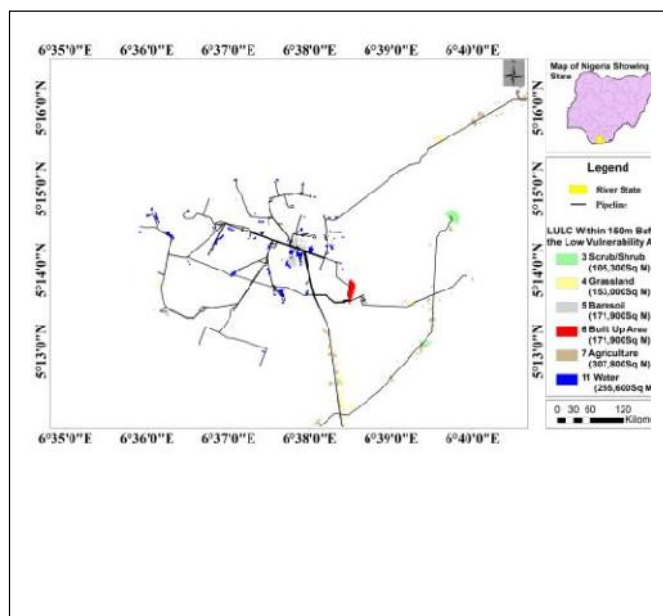


Fig 29.0. Susceptible habitats at risk within medium vulnerability surface(150 meter scenario)

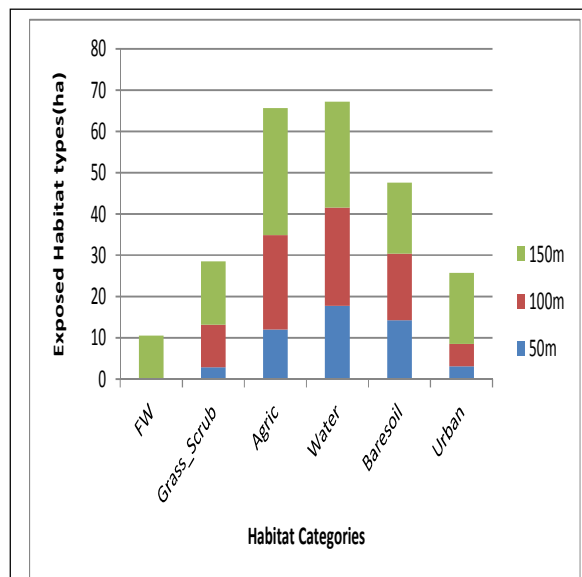


Fig 30.0. Area(ha) of Susceptible habitats at risk within low vulnerability surface(50, 100 and 150 meter scenarios)

The paper provides a template for simulating the movement and impact of potential oil spill on habitats especially as these habitats are interspersed and juxtaposed between composite oil facilities. The result of interspersed and juxtaposition is such that the distribution of landuse and landcover types will respond differently in a gradient of distances as they act as distance modifying factors. The vulnerability surface raster simulated ten classes with the highest surface equivalent to 18% of the total area of study (108 sq km). The neighborhood regions of vulnerability from the highest 18% show a gradient of accumulated surfaces at relative percentages of 16.1%, 14.7%, 15.1%, 6.5%, 9.4%, 7.9%, 5.0%, 4.5%, 2.6%. The output of the accumulated surfaces defined the overall zones of vulnerability and outlined the geographic area of interest for contingency planning scenarios. Potential categories of vulnerability within these areas of interest can be identified, characterized and quantified in order to set response objectives and support decision making during a response.

The paper examined ways to apply the model output values to quantify site specific habitat datasets within each accumulated surface of interest. The overlay of the accumulated vulnerability surfaces over the landuse and landcover types within a 50 meter, 100meter and 150 meter buffers generated three outputs with different applications. The first output demonstrated the capacity of each vulnerability surface to delineate and quantify susceptible habitat features at risk that best represent unique conditions and patterns. Each habitat feature at risk was processed as an estimate at pixel levels throughout the continuous vulnerability gradient. Within the 50 to 150 meter buffers accurate quantification of the sensitive habitats at risk at each vulnerability scale were possible as each accumulated surface was divided by the pixel resolution. Contingency planning can therefore combine techniques that are grounded in raster based processing to generate vulnerability surfaces as they suffer less from issues related to scales of agglomeration or Modifiable Areal Unit Problem [10-13]. The map produced at various scenarios and at various scales can be used to convey essential information for a wide range of operational planning information.

6.0 Conclusion

The paper provides a spatial model of vulnerability generated from the metrics of Euclidean distance and the cost of migration of a potential oil spill across different landuse and landcover types. A Vulnerability surface was generated that represent the total function risk modeled as the iteration of aggregate oil facility cost surface (likelihood) and environmental sensitivity cost surface (consequence). The vulnerability surfaces generated which were classed into high medium and low were used to extract susceptible landuse and landcover types from a 50meter to 150 meter scenarios, using GIS overlay techniques. Each vulnerability surface within the defined buffers was able to quantify pixels of landuse and

landcover types susceptible to the risk of a potential oil spill. The raster pixel processing techniques that generate accumulated (vulnerability) surfaces is proposed as a potential powerful tool for Contingency planners. Pixel scale resolution allows a level of detail for scalable area scenario based modeling for intervention planning.

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