

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

Abstract

Natural habitats vulnerability to Oil spill 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 at an appropriate scale and spatial resolution, raster-pixel based vulnerability surfaces have the potential to be effective tools in Contingency planning and response to inland oil spills.

Keywords: Oil spill, Natural Habitats, Landuse, Landcover, Vulnerability, Raster, GIS

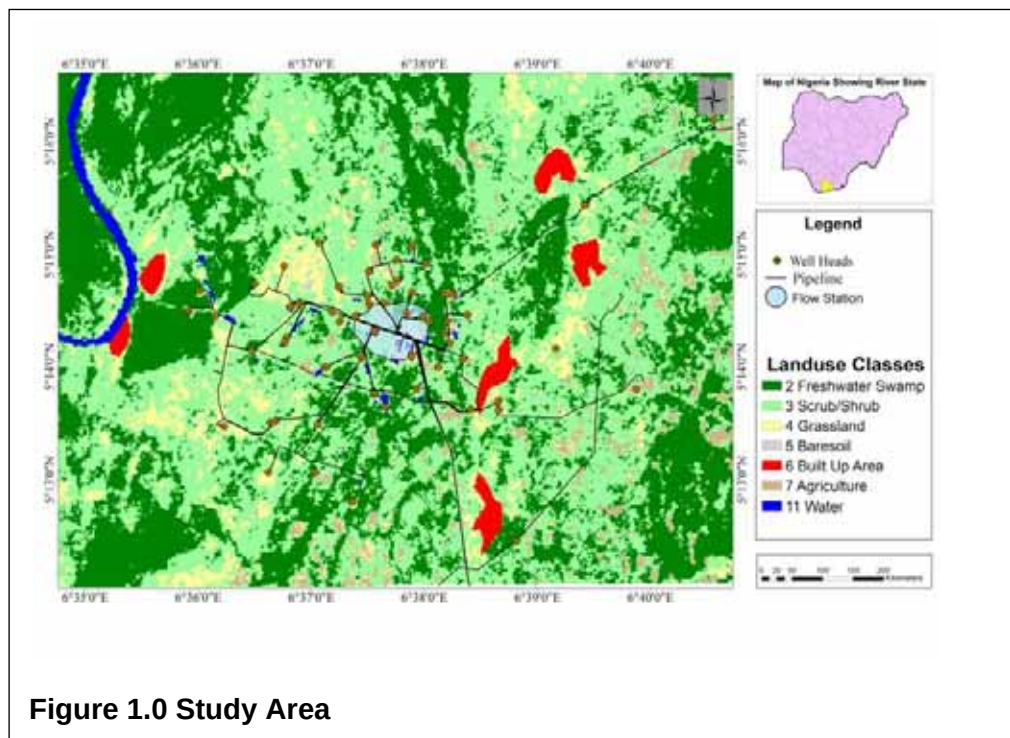
1.0 Introduction

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) covers a total of 10,899.99 hectares containing different land use and land cover 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.



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 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

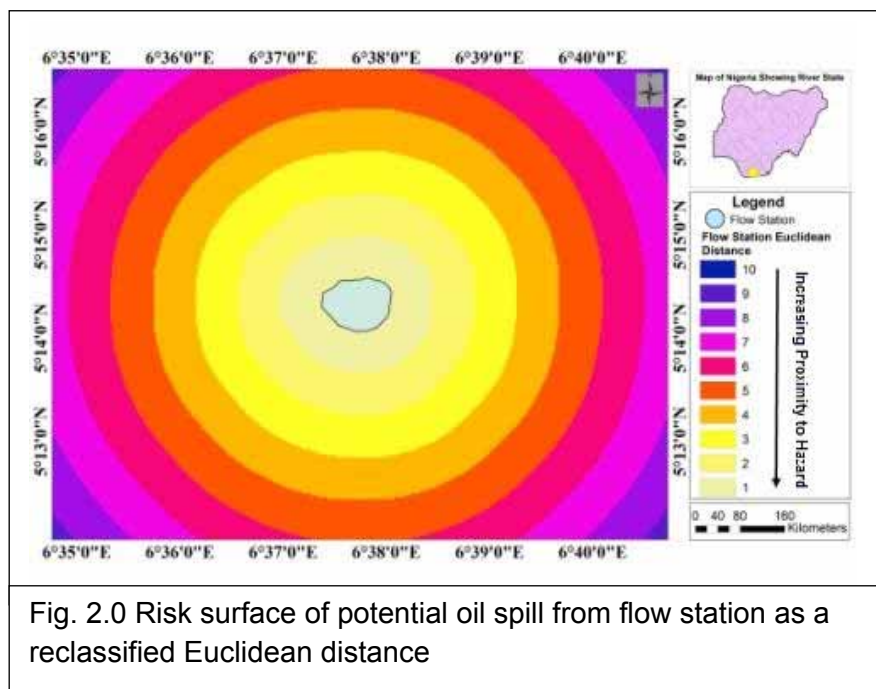
Landuse-Landcover	Sensitivity Values	Sensitivity
Water	1	Low
Grass/ Baresoil	4	Low
Built-Up Area	5	moderate
Agricultural Land	6	moderate
Regrowth Vegetation	7	High
Freshwater Swamp	10	High

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.



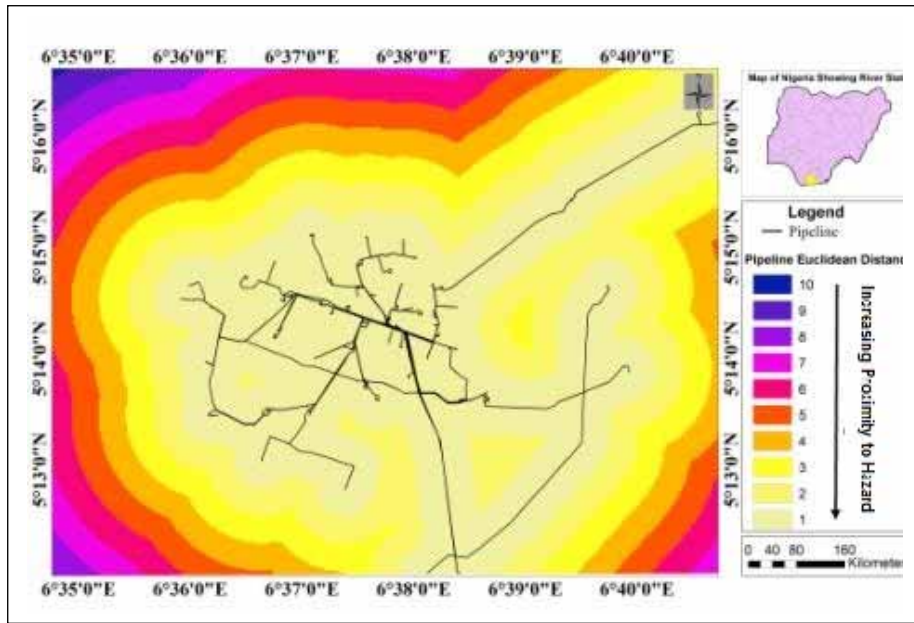


Fig. 3.0 Risk surface of potential oil spill from pipelines as a reclassified Euclidean distance

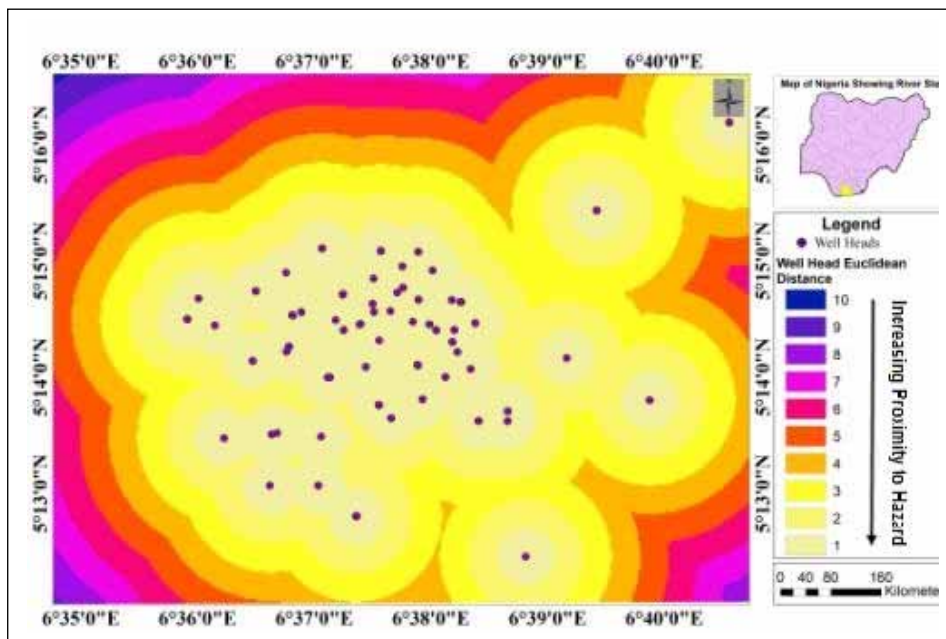


Fig. 4.0 Risk surface of potential oil spill from wellheads as a reclassified Euclidean distance

Figure 5.0 shows the raster surface that defines the cost or impedance of potential oil spill to move planimetrically through each cell of the landuse and landcover features. This cost (or impedance) is a factor of two variables: Landuse and land cover. The denser the vegetation of landuse features the more cost of migration.

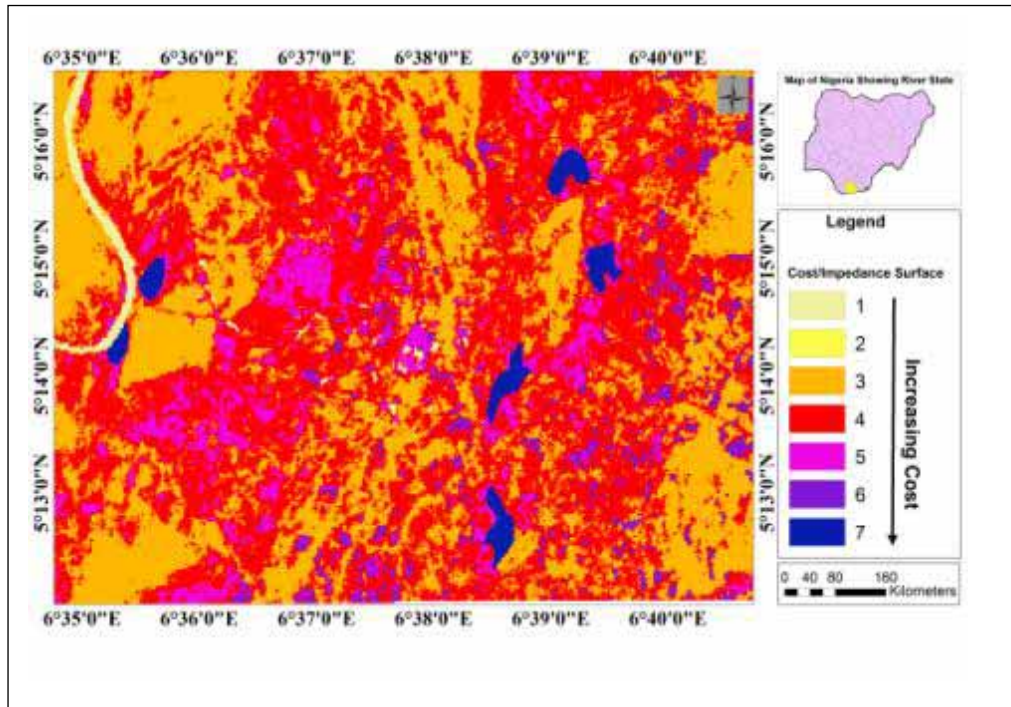
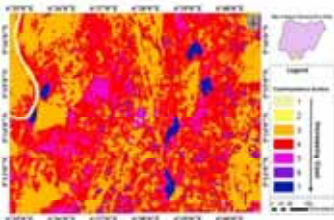
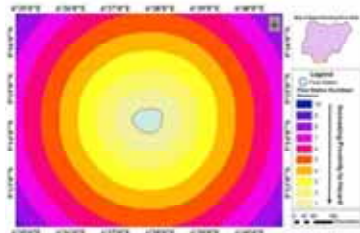


Fig. 5.0 Cost distance surface raster classified according to relative impedance

In Figs. 6.0, 7.0 and 8.0 are shown the results of iterating cost distance and Euclidean distance 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 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. 9.0. This represents the composite cost surfaces which are the coincidental migration cost of each data source (flowstation, pipeline and wellheads). This 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. 10.0 and represents the iteration of the composite cost 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 surface of potential oil spill from flow station as a reclassified Euclidean distance



Cost distance surface raster classified according to relative impedance

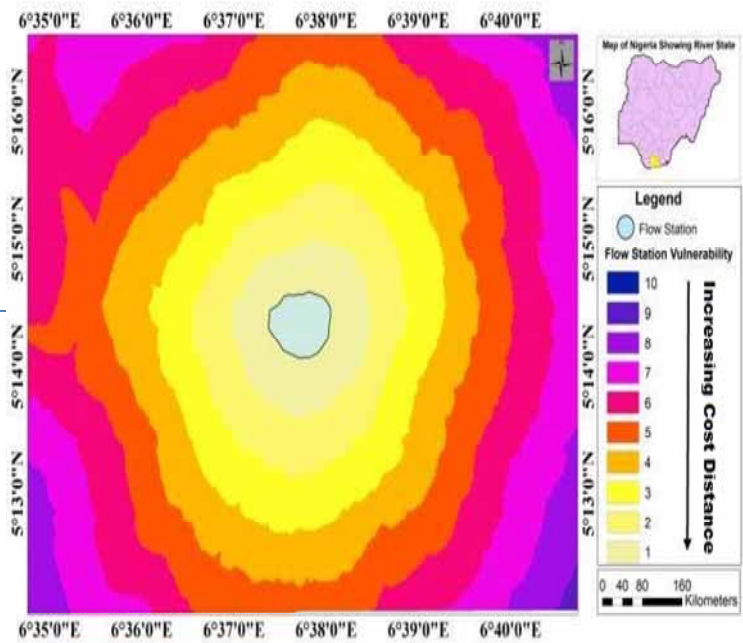
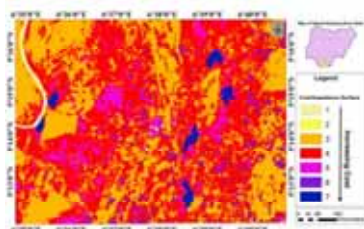
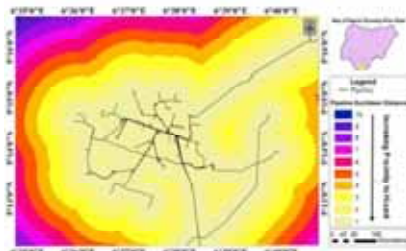


Fig. 6.0 Aggregate Cost Risk surface for Flowstation facilities

Euclidean surface of potential oil spill from pipelines as a reclassified Euclidean distance



Cost distance surface raster classified according to relative impedance

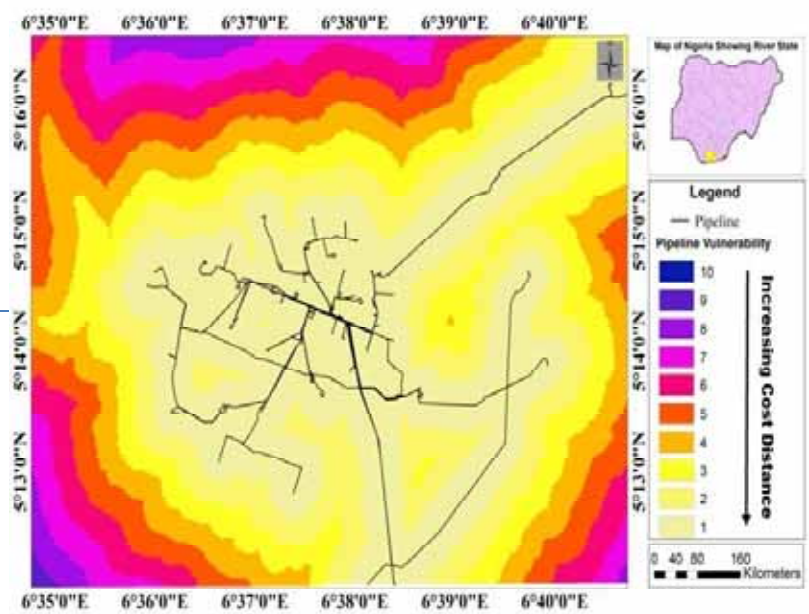


Fig. 7.0 Aggregate Cost Risk surface for pipeline facilities

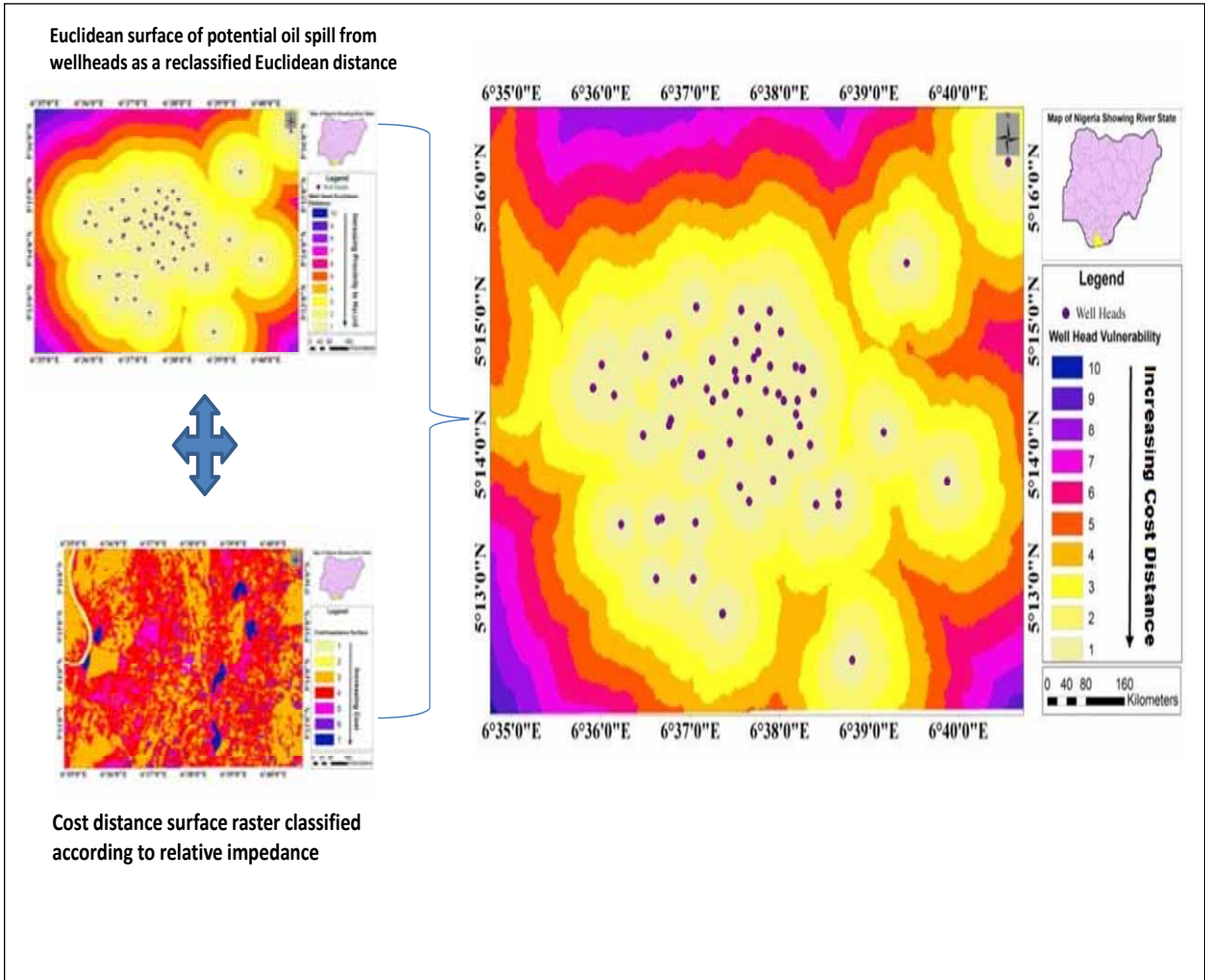


Fig. 8.0 Aggregate Cost Risk surface for wellhead facilities

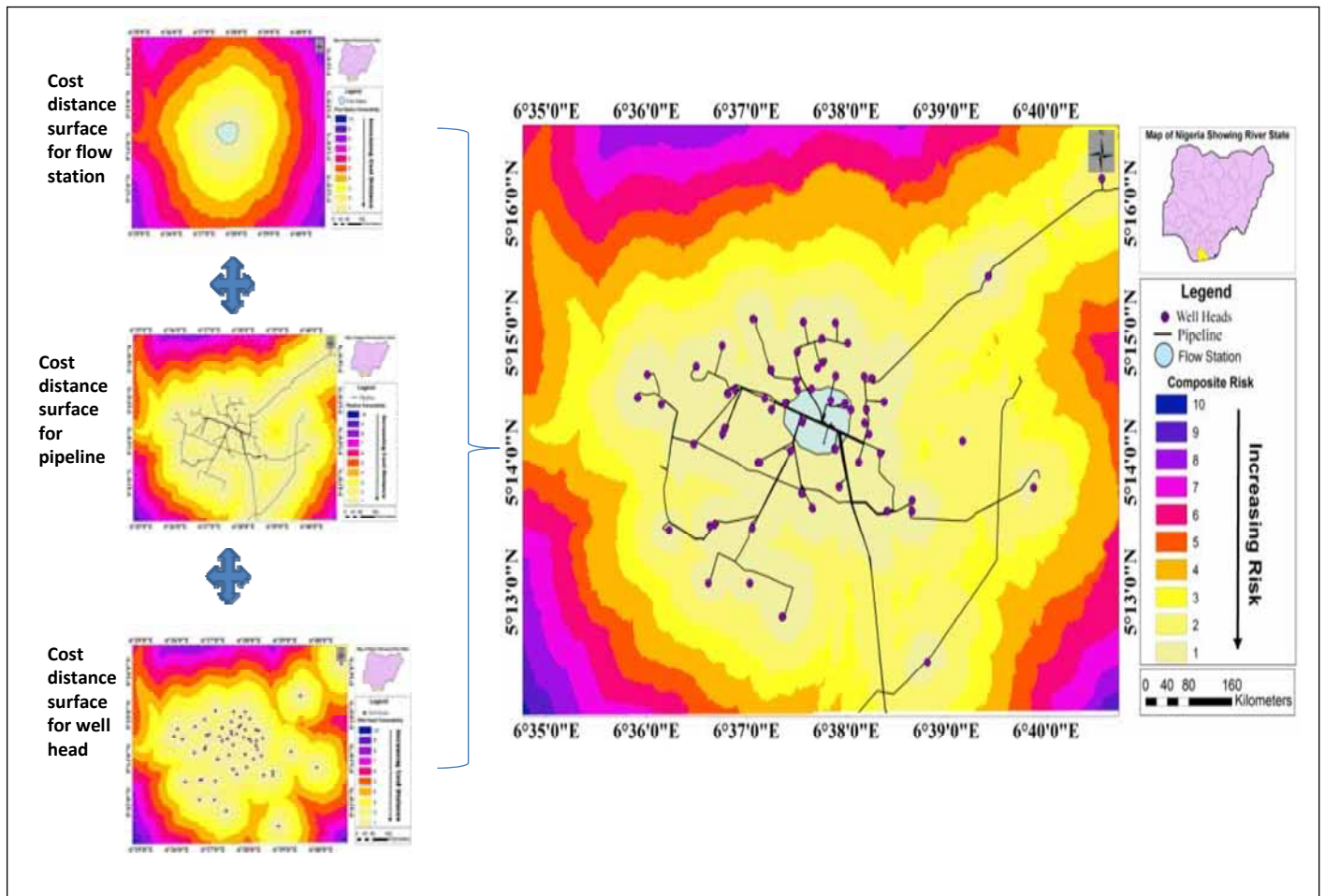
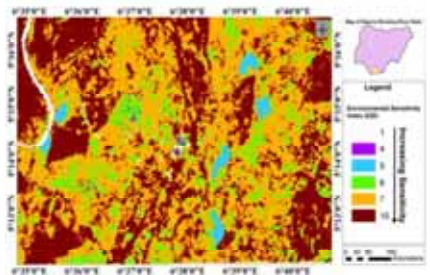
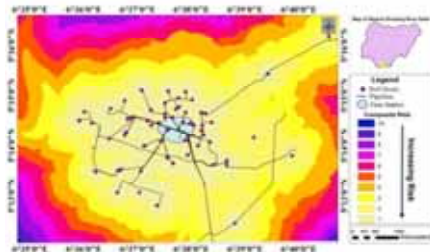


Fig. 9.0 Composite Cost Risk surface of facilities, pipelines and wellheads to potential spill oil migration

Composite (flowstation, pipeline, wellhead) oil spill migration risk surface



Consequence cost surface from environmental sensitivity values

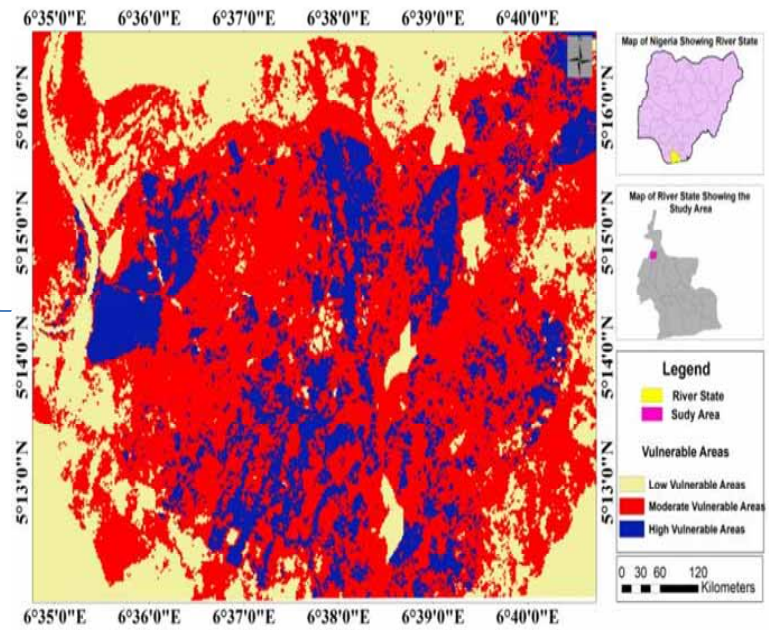


Fig. 10.0 Vulnerability cost surface

4.1 Habitat Surface Vulnerability Analysis

Figure 11.0 show the distribution of classes of vulnerability surface within a simulated scenario of 50-150 meters. The area covered by each vulnerability surface ranged from 130-409 hectares for high vulnerability surface; 502 -1147 hectares for the medium vulnerability and 50-107 hectares for areas covered by low vulnerability.

In Figs. 12.0 to 14.0 the proportions of the sensitive habitat features likely to receive impact are shown for each vulnerability surface within the simulated buffer zones of 50-150 meters. In fig 12.0 the model shows proportions of sensitive landuse/landcover within the high Vulnerability zone in the simulated buffer zones to range from 130-408 hectares. In an overlay process this was spatially coincident only to the freshwater swamp forest. In Fig. 13.0 the proportions of sensitive landuse/landcover within the medium Vulnerability zone in the simulated buffer zones ranged from 1.1-381hectares at 50 m zone; 1.7-674 hectares at 100 meters and 2.7-937 hectares at 150 meters. In an overlay process this was spatially coincident to four habitats abundant in decreasing order of Regrowth Vegetation> Grass/Scrub >Agriculture >Freshwater Swamp. In fig 14.0 the proportions of sensitive landuse/landcover within the low Vulnerability zone in the simulated buffer zones ranged from 0-18 hectares at 50 m zone; 0-24 hectares at 100 meters and 11-31 hectares at 150 meters. In an overlay process this was spatially coincident to six habitats abundant in decreasing order of Water>Agriculture>Baresoil> Grass/Scrub>Urban>Freshwater Swamp.

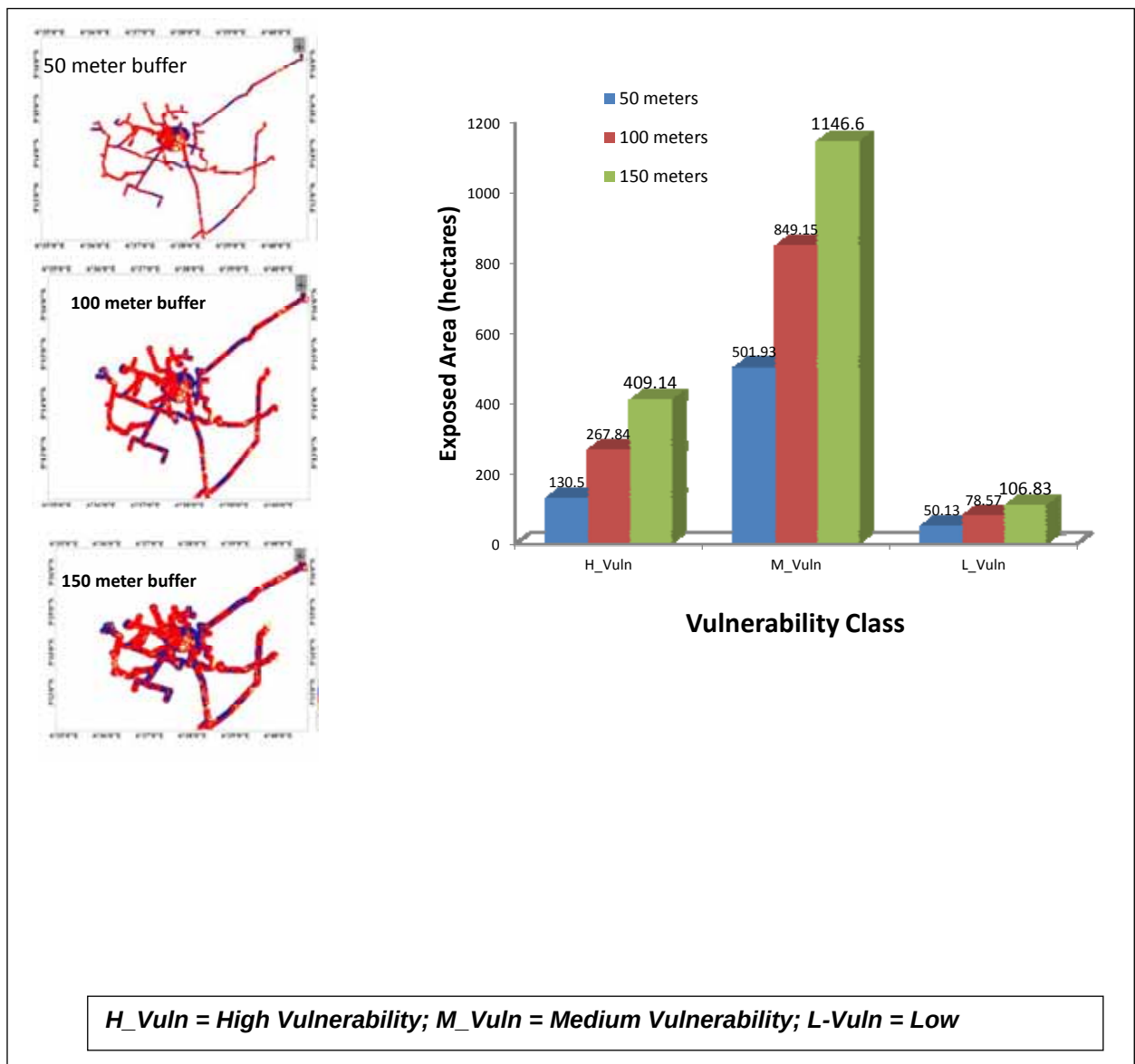


Fig. 11.0 Surface area of Vulnerability classes (ha) within 50m -150m buffer zones

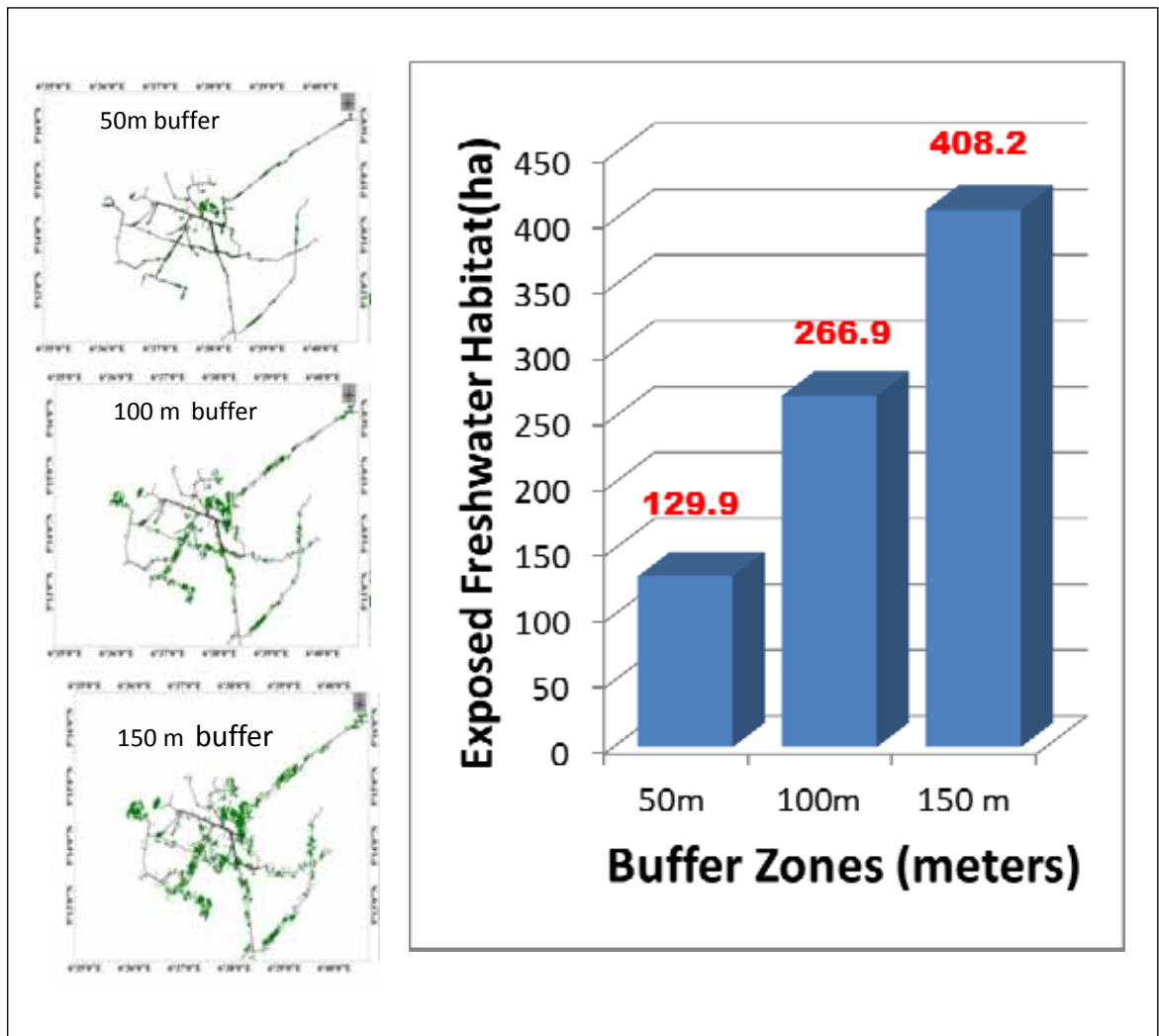


Fig. 12.0 Area (ha) of susceptible habitats within high vulnerability surfaces (50, 100 and 150 meter buffers)

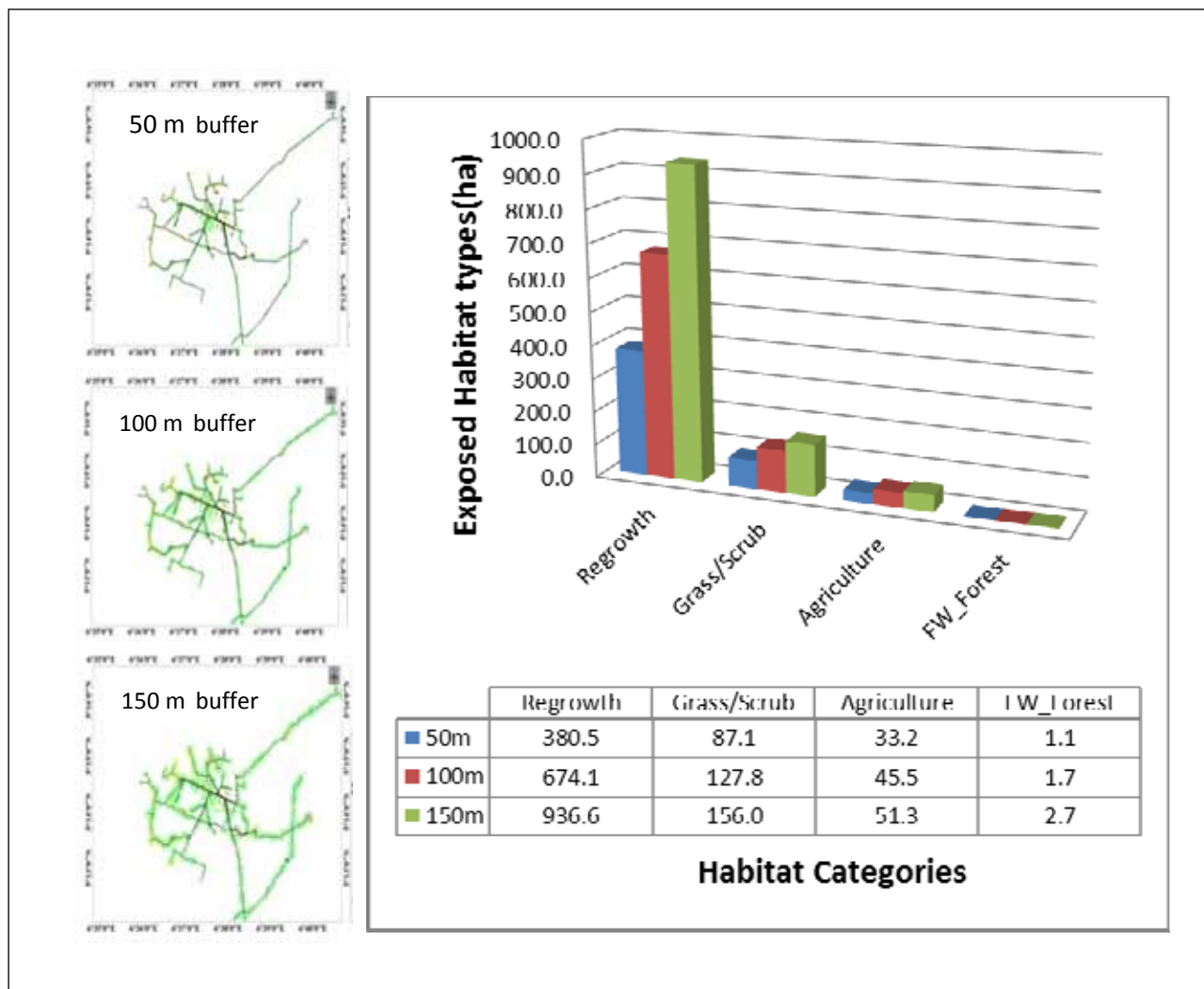


Fig. 13.0 Area of Susceptible habitats at risk within medium vulnerability surface (50 meter buffer)

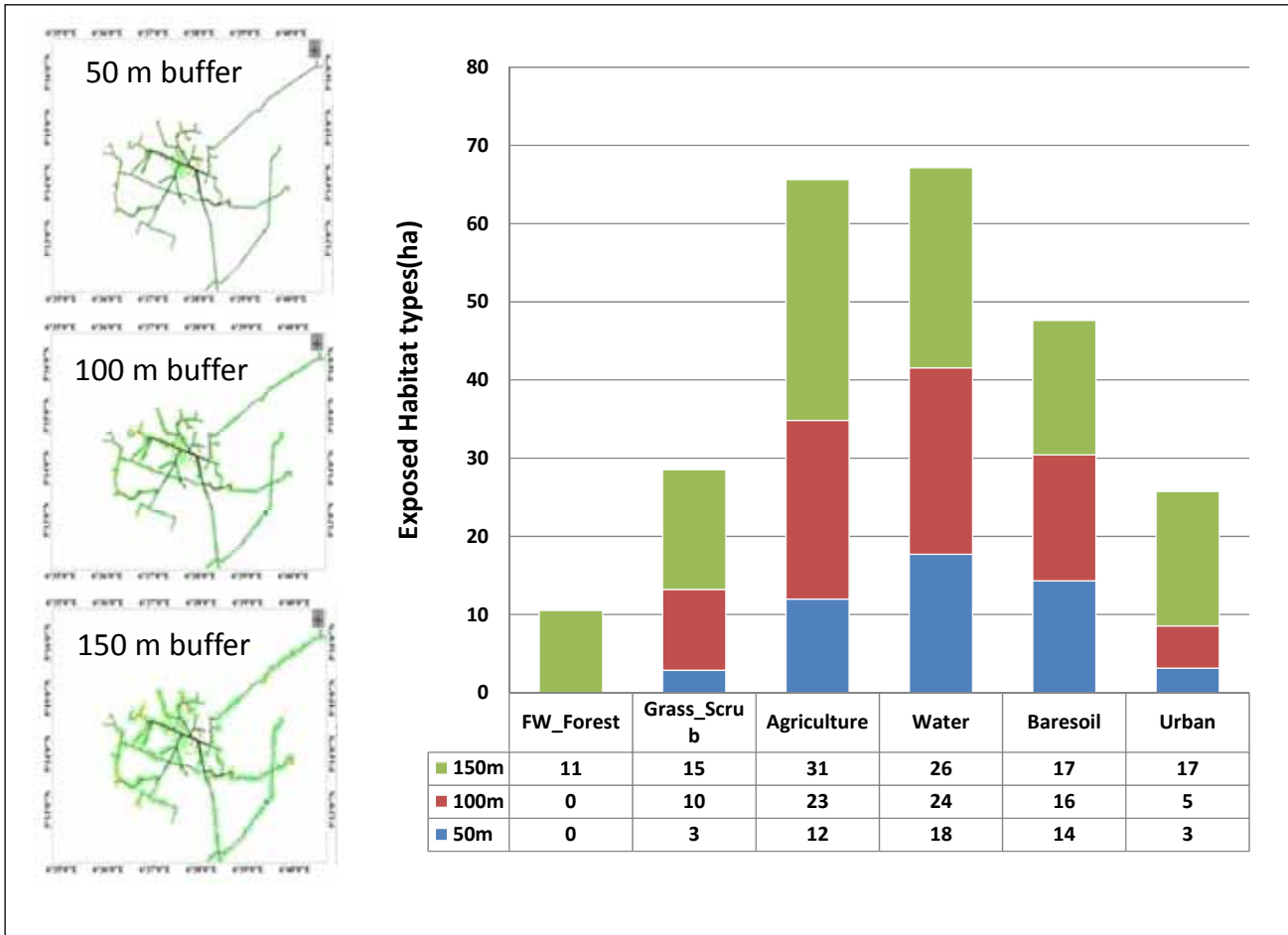


Fig 14.0 Area (ha) of Susceptible habitats at risk within low Vulnerability surfaces (50, 100 and 150 meter buffer zones)

5.0 Discussion

Euclidean and cost distance modeling were metrics derived from raster data to calculate the classes of vulnerability of sensitive habitats (plant biodiversity) features to potential oil spill. Raster-based vulnerability surfaces have proven to be effective in the study of vulnerability of environmental features [10-13]. The vulnerability surfaces derived from iteration of accumulated and consequence surfaces provided insight into the relative proportion of total area of interest necessary for protection.

The paper examined ways to apply model output values to quantify site specific habitat datasets within each vulnerability surface (VS) of interest. The overlay of the VS over the landuse and landcover types within a 50 - 150 meter buffers generated outputs with different applications. The observable output was a demonstration of the capacity of each VS to delineate and quantify susceptible habitat features at risk that best verify unique conditions and patterns critical to protection planning. Each habitat feature potentially at risk was processed at pixel values throughout a continuous vulnerability gradient making accurate quantification of the sensitive habitats likely at risk possible.

From pixel-based analysis, the ratio of the vulnerability classes (high/medium; high/low and medium/low) within the simulated buffer zones (50m, 100m and 150m) were similar signifying little variation in the distribution of distance modifying factors. Since the landuse and landcover features were used to simulate distance modification, the effect of their interspersions and juxtaposition had little effect in the gradient of distances from 50m-150m. Thus for any portion of area of interest a user can isolate the cost of potential oil spill mobility and spatially process cost distances that are significantly influenced by changes in landscape features. Likely landscape features analyses *per class* of vulnerability were identified with different trends in sensitive habitat variables. Surfaces with high vulnerability were likely to impact only freshwater swamp forest areas which have the highest environmental sensitivity. However this becomes discontinuous as the distance of the buffer increased from 50 m to 150m indicating the effect of the fractal dimension of habitat elements. The likely habitats derived from surfaces with medium and low vulnerability were a mixture of medium and low sensitive landuse and landcover. This served as an important metric to describe the mosaic nature or the degree of interspersions and juxtaposition of habitat elements when measured at the pixel resolution of the imagery data. Thus the model provided behavior analyses of a potential oil spill and the relationship to sensitive landscape features. By using raster based pixel analyses the model also provided

opportunity for contingency planners the metrics for evaluating the patch and connectivity of the sensitive landscape features. 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 [14-17]. The map produced at various scenarios and at various scales can be used to convey essential information for a wide range of operational planning. 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.

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 represents 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 50 meter 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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