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Assessing Environmental Hazard Vulnerability from Integration of Lineament from Aeromagnetic and Monte Carlos-Simulated Permeability Model from Borehole Data in Benin City, Nigeria

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Abstract
The study tries to evaluate environmental stability and hazard vulnerability in Benin City by predicting the environmentally stable and weak zones. Characterizing the near-surface geo-hazard conditions using the routine traditional Engineering/geotechnical studies offers limited/localized coverage, hence the challenge from the devastating effects of geo-hazard areas persists in the study area. Besides being cost intensive routine geotechnical technique offers limited solution, hence ineffective. The present study employs analytical method that provides a predictive model of the stability/vulnerability potential hence providing opportunity for possible preventive measures with extensive coverage in the entire area. Both aeromagnetic and borehole data were used while StratraExplorer and Geosoft software were used to run the analysis, simulation and integration to predict the environmental hazard vulnerability. The lineament feature from aeromagnetic data and effective permeability coefficients obtained from numerical simulations of the borehole data were integrated to predict stable and weak zones that determines the environmental hazard like flooding Result of the aeromagnetic analysis yielded good quality total magnetic intensity map reduced to the equator. Lineament maps generated from the total magnetic intensity data showed north, northeast and northwest as the dominant orientations. Six shale/clay horizons were delineated in forty five boreholes located in the area. The average thicknesses of the shale/clay ratio in the various horizons were subjected to twenty eight thousand simulation using Monte Carlo Simulation to yield high quality effective permeability coefficients distribution model. The result of the integration of the lineament and the effective permeability models yielded a hazard distribution/vulnerability model. The model shows that the central area is most vulnerable while the adjacent areas are moderately vulnerable with pockets of isolated areas with the least vulnerability. This thus effectively classified the study area in terms of the hazard/flooding vulnerability.

Keywords: *Monte Carlo simulation, effective permeability, total magnetic intensity, lineaments, geotechnical investigation, environmental hazard, flooding, stability/vulnerability potential.*

Introduction

Geological structures and their orientations become complex at joints, lineaments and fractures that constitute vehicles to hazard like flooding in an area. The vulnerability of the study area, Benin City to flooding is being investigated using information from both Geophysical (aeromagnetic) and borehole (electrical conductivity and lithology) data. Joints, lineaments and fractures represent zones of weakness and uneven settlement. Loading and unloading in areas with prevalent weakness and uneven settlement increases their inherent weakness and uneven settlement. Lineaments can be mapped through several means such as field geological mapping, automatic extraction from topographic maps, digital elevation map, seismic reflection maps and aeromagnetic data. An approach utilizing Monte Carlo simulation on aeromagnetic data to generate lineaments and integrating it with the effective permeability coefficient model from borehole data was performed to assess the geo-hazard vulnerability in the study area. A number of literature provide valuable insights into the stability of near surface environments, including factors related to geological structures like lineaments, slope stability among others. The stability or otherwise of the near surface environment is closely related to the degree of cohesiveness of the underlying geologic formation. Routinely, engineering geotechnical technique has been employed to map the stability of soils for engineering construction. Accordint to Jha *et al*. (2012) a common natural hazard is the flood which affects most cities worldwide. Consequences of flooding may include economic losses accounting to up to 30% globally (Hallegatte *et al*., 2013). Projections of the global population to be affected by flooding is estimated to vary from 1 million to 25 million in 2050 (Sachs, 2006). Studies also show that about 20% of Nigerian population has been affected by flooding disasters (Oyekale, 2013). For instance, Niyogi (1987) studied the stepped erosion surfaces of Chhotanagpur Plateau and highlighted the relationship between the errosivity of the terrain to the geological features. Ravindra (1997) studied the drainage morphology in relation to its correlation to geology, geomorphology and groundwater prospects in Zuvari Basin, South Goa, using remote sensing and GIS. The result highlights the relationship between geological features, geomorphology and groundwater. Cilona *et al*., (2016) had investigated the implication of lineaments on groundwater flow and containment. The result shows a relationship between the lineament orientation to the groundwater flow and contaminant transport in the Santa Susana Field area. Understanding these features is crucial for managing groundwater resources and assessing the contaminant potential.

Al-Nahmi et al., (2016) used remote sensing technique to extract lineaments in Al Magbrabah area, Yemen. The result shows the efficacy of the tool in extraction of geological feature. Adiri et al., (2017) also extracted lineament from both ASTER and satellite remote sensing data at the Sidi Flah-Bouskour inlier, Morocco and concluded that the later offered higher resolution of geological features than the former. Hermi et al., (2017), utilized satellite image to interpret geologic structure in North Tunisia. The result shows the efficacy of the tool in identifying the geologic features. Akinluyi et al., (2018) investigated the influence of lineaments on groundwater flow in basement complex and established that the lineament structures offer a structural control to the groundwater flow in basement areas. It concluded that areas with more lineaments yielded more water than areas with less lineaments. Boutirame et al., (2019) mapped the geological structures using aeromagnetic and remote sensing techniques and found the results useful in the identifying the geologic structures in the Karstic Massif of Beni Mellal Atlas, Morocco. Shebi and Csámer (2021) successfully extracted lineament from digital elevation maps and the result shows that it is a good tool for lineament extraction and sheds lights on the spatial context of lineaments. Nag (2005) utilized the lineament density and hydrogeomophology to delineate groundwater potential zones at Baghmundi block in Purulia district, West Bengal.

Omowumi (2022) discussed the application of geophysical investigation for structural studies. The stability/vulnerability in the face of diverse environmental conditions therefore vary. Vulnerability to hazards of a near surface is closely related to the relative stability or otherwise of the geologic conditions in the near surface. This in turn determines the level of environmental degradation factors such as flooding, contamination, erosion among others. Increases with increase in the service stress and life of engineering structures like buildings, bridges, roads among others, are greatly influenced not only by their constituent materials but by the underlining geological structures and their orientations. Analysis of failed engineering structures had shown that failure rate is not uniform. The engineering structures were construction with the same materials and methods but failure expressions gave some insights that an extra factor is involved. This extra factor can be attributed to the underlying geological structures and their orientations. Alemayehu et al., (2022) undertook a multichannel analysis of surface waves to estimate the shear wave velocity for engineering characterization of soils in Southern Ethiopia. They report a relationship between the soil property and the shear wave velocity.

Geophysical and hydrogeological methods have been used by different researchers to define the thicknesses, shapes, horizons and subsurface layers in both crystalline and sedimentary terrains. Longe et al (1987) used well logs, pumping test data, borehole yields and water quality data in Lagos Metropolis to define the Metropolis's aquifer types with their average corresponding transmissivities. Asiwaju-Bello and Oladeji (2001) produced the hydrostratigraphic model of Lagos Metropolis using geologic well logs, pumping test data and static water level and the model delineated the aquifer type to three with varying hydrogeological properties. Akujieze and Oteze (2007) studied on the Benin Formation aquifer, estimating it aquifer's yields and transmissivity values. They also delineated the aquifer type. Offodile (2002) concluded that the Benin Formation aquifer is be very thick, extensive and unusually very permeable using lithology logs and pumping test data from the formation. The transmissivity values, storage coefficient and porosity were also estimated. Alile et al (2012) stated the major aquifer in the Ikpoba Okha area to be sand of vary depths. Numerical method has been used by different researchers to characterize different lithologies and estimate permeability. Desbarats (1987) estimated the effective permeability of Assakaro fluvial sandstone in Central Sahara using the turning band method. Haldersen et al (1982) estimated the effective block permeabilities in sandstone using Monte Carlo simulation.

Dmitry et al (2010) calculated effective permeability numerically using Double Randomization Monte Carlo

Simulation. Xiao, et al., (2018), developed a fractal model for water flow through unsaturated porous rocks. Xu, andYu, (2008), developed a new form of permeability and Kozeny-Carman constant for homogeneous porous media by means of fractal geometry. . Yu et al (2002) produced a fractal permeability model for bi-dispersed porous media. Yu et al (2005) estimated the permeability of fractal porous media using Monte Carlo Simulation.

The lithology of the study area is composed of ferrugenised sandstones, medium to coarse sandstone with intercalation of clay lenses, clay and gravely sandstone with intercalation of clay lenses. The estimation of effective permeability coefficient will be based on the distribution and thickness of the clay lenses. The clay lenses will be used to delineate the two aquifer systems of the area. The first and upper aquifer is partly unconfined and partly confined with varying thicknesses. The effective permeability values will be estimated by numerical simulation of clay lenses in the study area using Monte Carlo simulation. Where different orientations of lineament interact, complex effects were observed. These effects include varying or very different hydraulic head, aquifer transmissivity, clay thickness and total magnetic intensity. Engineering structures in such locations tend to have longer service life. Instability and uneven settlement characterized areas having chaotic or very different effects. The service life were greatly reduced in such areas. The effective permeability obtained from lineament orientation, total magnetic intensity, and thickness of clay gives a comprehensive geotechnical insight for site investigation before the construction of engineering structures. This method is cost effective and very fast.

The environmental conditions are routinely conducted using geotechnical approach, which relies on limited geotechnical data sampled at different depths and sparse drill holes. This limits the coverage of the method to only small areas. In the present study area, the study focuses on delineating the lineaments and effective permeability based on the thicknesses of the clay/shale lenses at the various depths, deriving the total magnetic intensity map from the aeromagnetic data, transforming the total magnetic intensity map into lineament map, then finally integrating both the effective permeability coefficient with the lineament map to produce/predict the environmental hazard vulnerability of the area based on the dissemination of weak and strong near surface materials. From the successes recorded so far by previous authors in characterizing the surface lithological features like lineaments from both geo-spatial and geophysical data, it becomes plausible to utilize the geophysical data to estimate the lineament density and distribution in order to model, on a relatively large scale, the vulnerability of the study area based on based on the established relationship between the lineament and degree of weakness or stability. In addition, this approach is expected to go beyond the limitation of using geotechnical method alone. This inherent limitation of the geotechnical method is due to limited sampling locations. The aeromagnetic data, on the other hand#, has a lot more wider coverage. The inherent weakness and uneven settlement will be analyzed using the effective permeability obtained from the borehole data (lithology and electrical conductivity) obtained from forty five (45) boreholes in Benin City. The total magnetic intensities and lineaments from aeromagnetic survey will be integrated to produce the vulnerability/stability map.

Location and Geology of the Study Area and the Niger Delta Basin

The study area is bound by Latitudes 6° 1' 00" and 6° 25' 00" N, Longitudes 5° 34' 00"E and 5° 43' 00" E. Fig. 1 shows the Location and Geology map of the study area, Benin City and insert map of Nigeria.

It is found in Niger Delta Basin which is an important petroleum province. The basin is generally agreed to be formed as a result of an aulacogenic activity initiated by the separation of the African and1 South American plates in the Jurassic. A trough was formed which was filled by a series of marine transgressions, regressions and deltas. Niger Delta Basin is recent. Short and Stauble (1967), Reijers et al. (1996), Nwajide (2006), among many others delineated the basin into three formations namely the Benin Formation, the Agada Formation and the Akata Formation. (Fig. 2). The Akata Formation is the oldest, followed by the Agbada Formation and the the Agada Formation and Benin Formation is the youngest. Akata and Agada Formations are between Eocene to Recent while the Benin Formation is between Miocene to Recent.

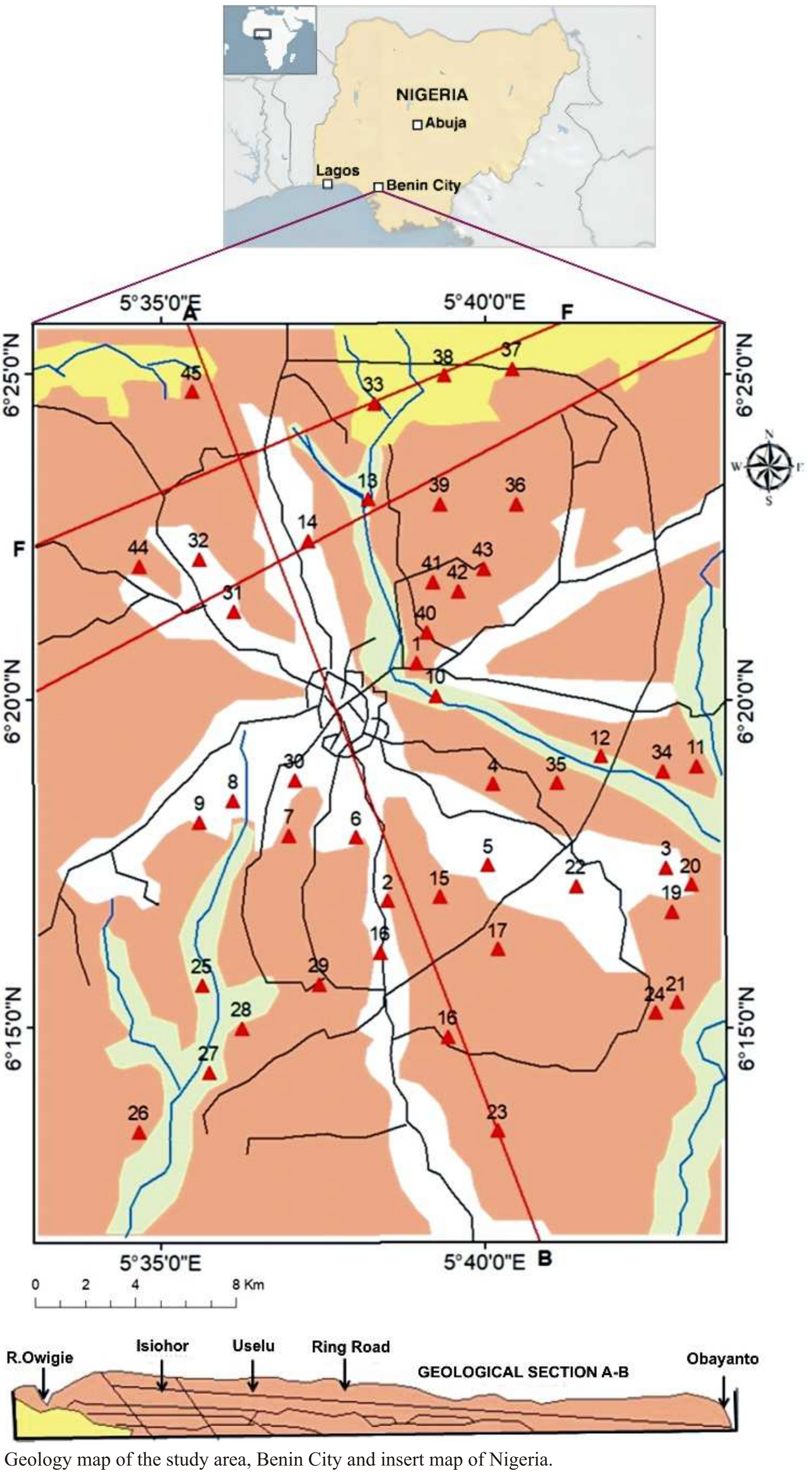

Fig. 1: Location and Geology map of the study area, Benin City and insert map of Nigeria.

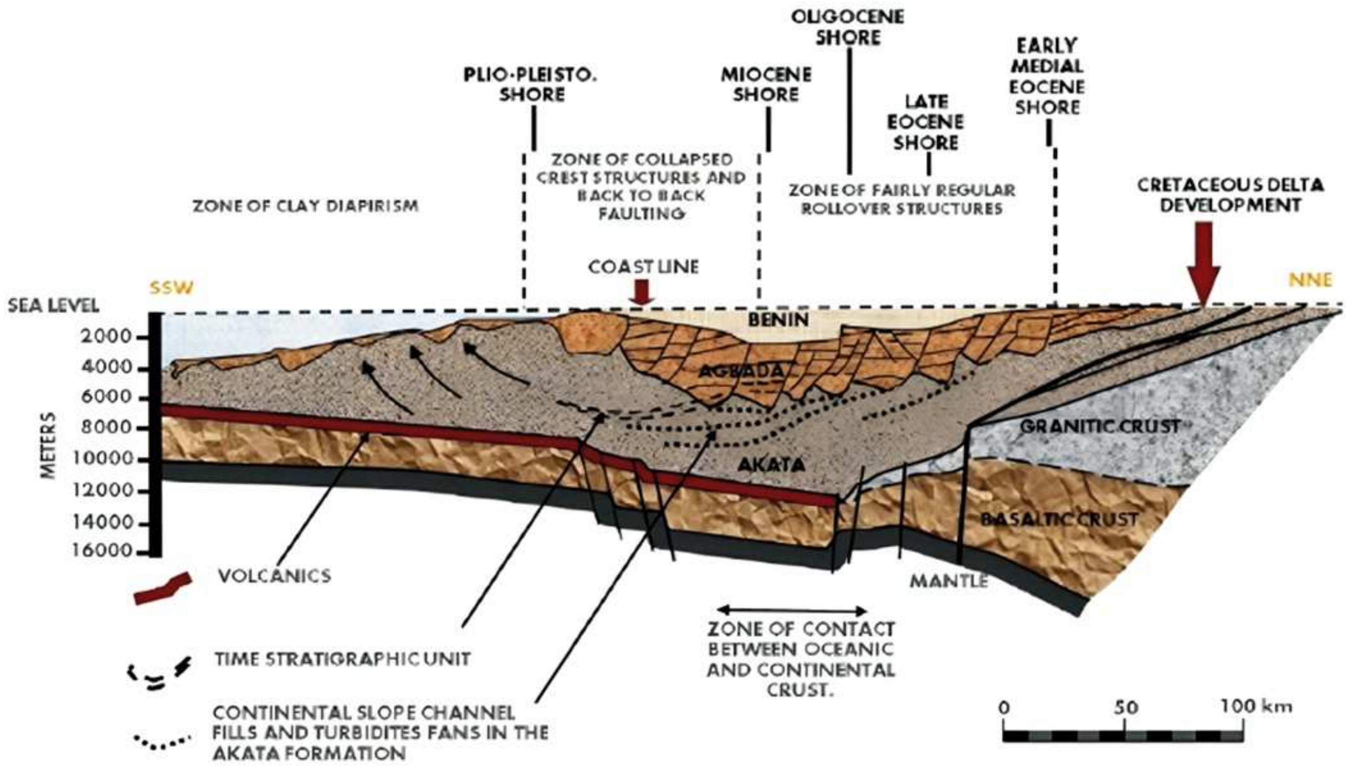

Fig. 2: Schematic Dip Section of the Niger Delta (Modified after P. Kamerling, from Weber and Daukoru, 1975)

In the study area, the Benin Formation is the topmost underlying Formation. It is dated from Miocene to Pleistocene. It cuts across the east of the Okitipupa ridge and the entire Niger Delta area. It is capped by reddish clayey sand followed by highly porous freshwater bearing, loose, pebbly sandstone. It also has varying thickness of clay and shale horizons that are discontinuous at different depth defined to be braided stream origin (Omatsola and Adegoke 1981). The Formation is about 2100 m thick and dips at between 2° - 8° south. The Benin region also consists of alluvium, drift and Ogwashi-Asaba Formation. The top is defined by reticulate mud cracks and reddish brown lateritic sand, with fairly indurated massive sand and clay. This is underlain by more friable pinkish-yellowish white sandstone. The grain-size is poorly sorted, often grading to gravelly to pebbly sands, clayey sands and clay. Alluvium are found along the flood plains of Ikpoba and Ovia. It consists of grayish-dirty white- sands, silts, clayey sands, gravels and plant materials.

Drifts are sediments still in motion and consists of light brown to yellowish silt, mudflows and sand derived from the parent material of the Benin Formation. The Ogwashi-Asaba Formations project upwards into the Benin Formation. It is made up of clay, sandstone with interbedded lignite in places. The sandy clays grades into the Benin Formation. The Ogwashi-Asaba Formation is exposed in stream channels at the northern parts of the Benin Region, west of Ekiadolor-Iwu and 4 km east of Utekon and north of Azalla. The formation appears reddish-yellow in colour due to the limonite content. The drainage pattern in the study area is shown in Fig. 3.

Materials and Method of Study

Forty five boreholes randomly distributed in Benin City and its environs were used for the study. The aeromagnetic data was acquired from Nigeria Geological survey Agency. The locations of the boreholes are in Fig. 4. The boreholes parameters of lithology and hydrogeology were obtained from Edo State Water Board, Benin-Owena River Basin Development Authority and private companies.

The aquifer transmissivity was obtained from the product of hydraulic conductivity and the thickness of the saturated aquifer. The method adopted involves analysis of both the geophysical (aeromagnetic and

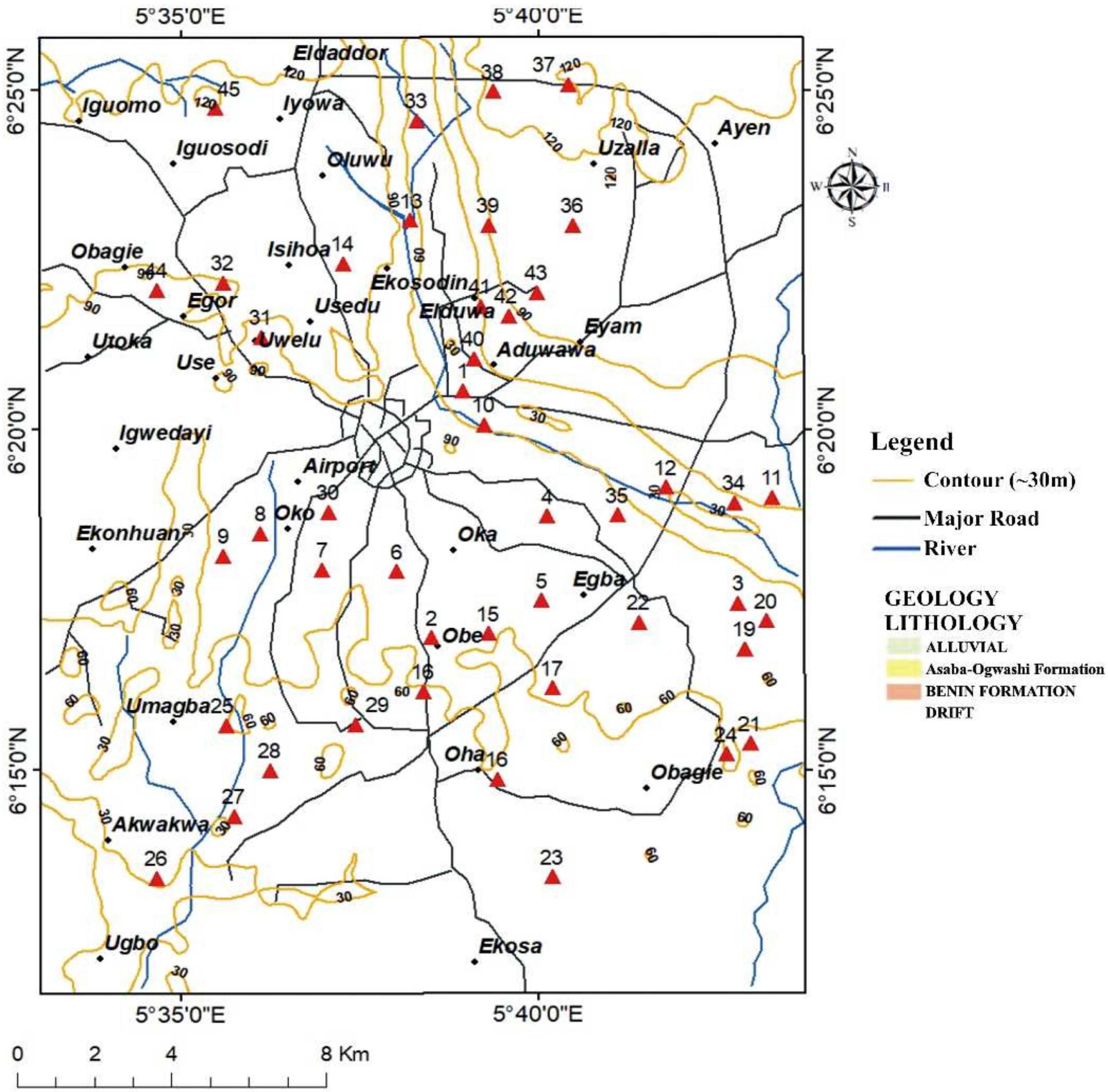

Fig. 3: Drainage map of the study area

borehole data and subsequently integrating the results of the two datasets to generate a hazard vulnerability map of the area. The workflow shown in Fig. 5 details the steps taken in achieving this study.

The borehole data were processed using StratraExplorer software. This software was used to process the various boreholes data. It also defined the various lithologies in each borehole. The lithologies in the various wells were correlated. These correlateable sequences were grouped in horizons as cross sections and used to generate the Effective Permeability Coefficient (E.P.C) scatter plot. The GeoSoft Oasis Montaj and Google Earth were used for the processing of the aeromagnetic and geospatial data to extract the lineament features of the study area. Both datasets, the E.P.C scatter plot and lineament data were finally integrated to produce the hazard vulnerability map. The detailed processes for each procedure issummrized in the workflow (Fig. 5).

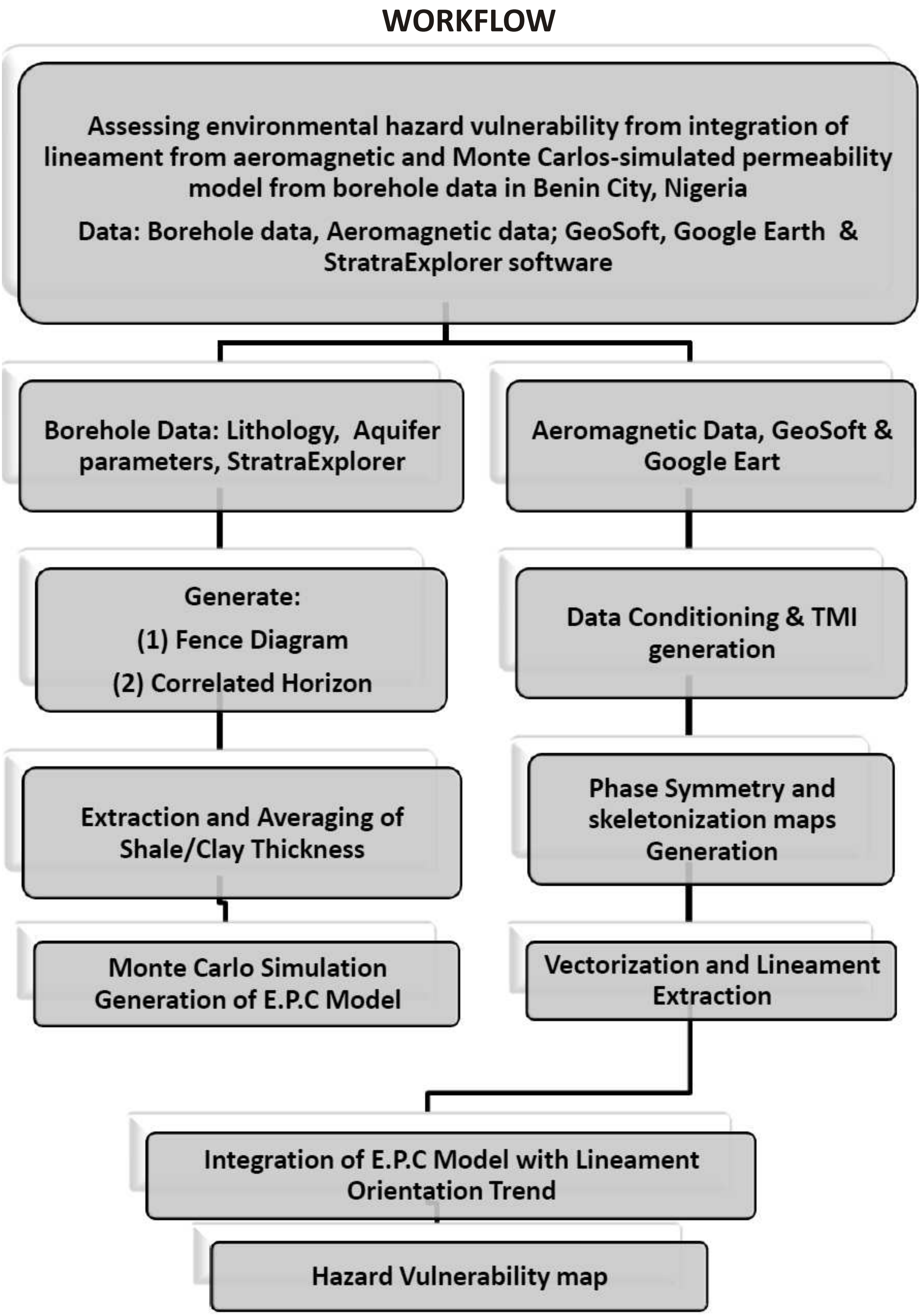

Fig. 5: Detailed workflow for the execution of the study.

1. Effective Permeability Coefficient (E.P.C). To simulate the E.P.C., six representative correlatable horizons were defined across the 45 wells in the study area. A set of 9 simulation parameters was defined based on the Monte Carlos simulation algorithm such as S-Thickness, Smax, Smin, S.average, S.SD, Final, below, above and E.P.C values respectively and run for each of the 6 horizons. The E.P.C values were generated twenty times using the clay/shale ratio at various depths of the 45 boreholes. These were input to create a database used to generate an E.P.C. scatter plot.
   A second set of process is the realization of lineament model from aeromagnetic data. The process is as follows:

2. Lineament Extraction Using GeoSoft and Google Earth software , the aeromagnetic data was first gridded to reveal the total magnetic intensity (T.M.I) anomaly in the study area in both x and y axis.. After reduction to Equator to reduce the effect of the regional magnetic effect on the TMI data. The TMI data is subjected to a further analytic signal processing through filtering to enhance the quality of the data by reducing the regional effects and increase signal to noise ratio. A further standard deviation generation over the area was performed on the data to express the variation of the data over the area. This is followed by phase symmetry processing, a filtering process employed to remove magnetic anomalies associated with shallow bodies which are not relevant to the features of interest. The phase symmetry was then skeletonized to further reduce the shallow anomalies and enhance deeper causative bodies. Finally, the data is further filtered in a process of vectorization to reveal the actual lineament trends (joints/faults, etc).

3. Data integration: Both datasets from above (effective permeability and lineament model) are finally integrated to produce the hazard vulnerability model that covered the entire Benin City and environs.

Results

Lithologic Mapping

The results of the lithologic mapping in form of correlateable horizons in all the wells were displaced in two dimension (2D) as panel diagram. These are shown in Fig. 6 (a-f).

Result from Monte-Carlo Simulation Algorithm of Lithology

The datasets for running the Monte Carlos simulation was input in the StrataExplorer software using the following forma and algorithm: For each given horizon, the following were run for the given 9 simulation parameters:

- S-Thickness. This is the average of the shale/clay thicknesses from a given or specific horizon. It is increase or decrease using a RANDOM IF statement. This increment or decrement was done twenty-seven times.
  S-Thickness = IF(RAND()>0.5,A3+1,A3-1)

- Smax. This is the maximum average shale thickness in a thousand simulation. This was done twenty-eight times.
  Smax= MAX(A:A)

- Smin. This is the minimum average shale thickness in a thousand simulation.
  This was done twenty-eight times.
  Smin = MIN(A:A).

- S-average. This is the average value of the shale thicknesses simulated a thousand times. This was done twenty-eight times.
  S-average = AVERAGE(A:A)

- S.SD. This is the standard deviation of the shale thicknesses simulated a thousand times. This was done twenty-eight times.
  S.SD = STDEV(A:A)

- Final. This is the shale thickness obtained after a thousand simulation. This was done twenty-eight times.
  Final = A1000

- Below. This is a COUNTIF statement. It gives a count of the number of the Final values below zero.
  Below = COUNTIF(F3:F30,"<0")

- Above. This is a COUNTIF statement. It gives a count of the number of the Final values above zero.
  Above = COUNTIF(F3:F30,">0”

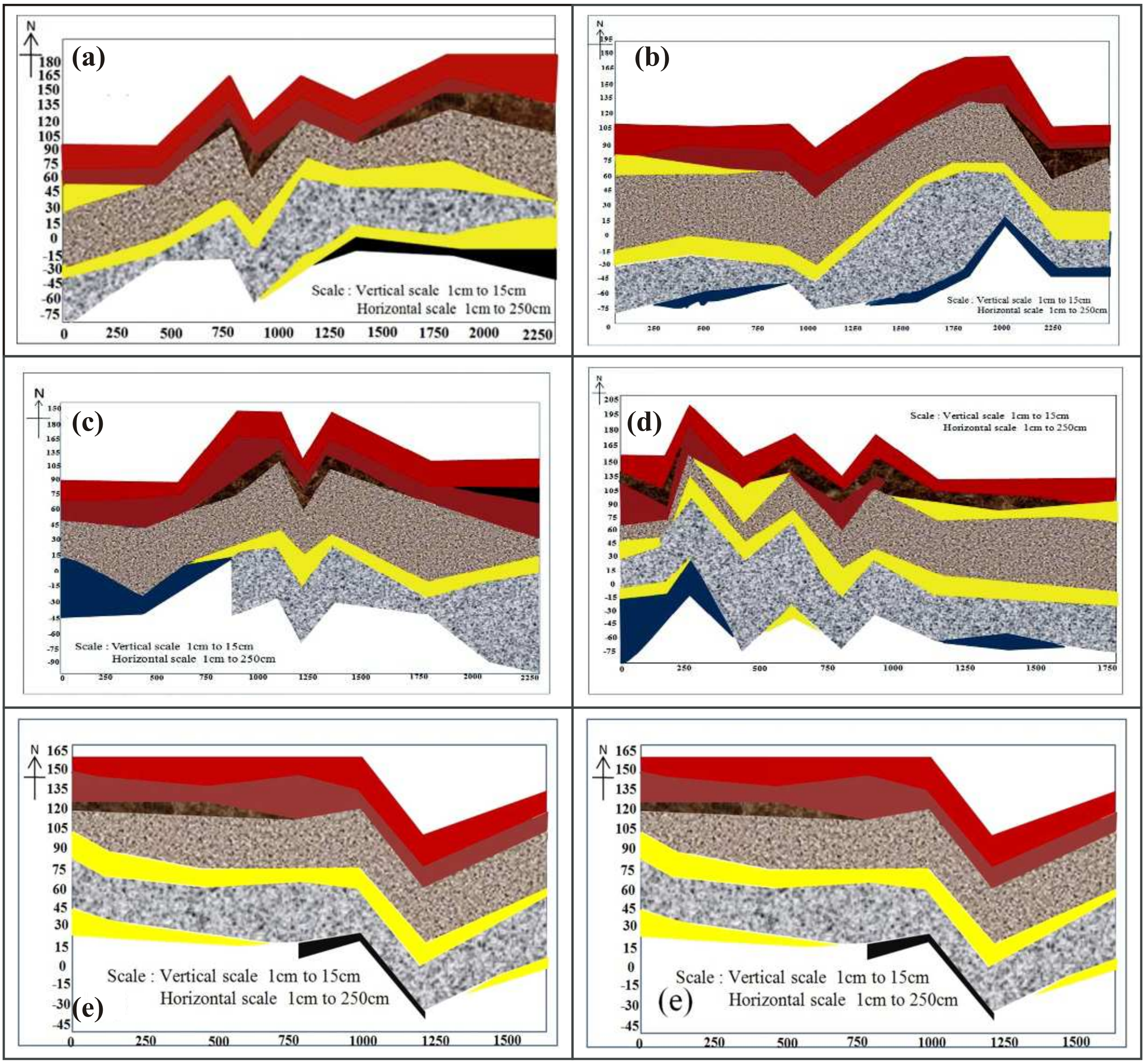

Fig. 6: Panel diagrams showing section along the chosen 6 horizons: (a) A-A', (b) B-B', (c) C-C', (d) D-D', (e) E-E' and (f) F-F' section using the StrataExplorer software

- E.P.C. This is the fractional change of "below" with respect to "above".
  E.P.C = (F32÷F33)x100

These series of simulation parameters were defined and applied to each of the six defined representative horizons chosen across the borehole in order to generate their simulation as listed above namely: S-Thickness, Smax, Smin, S.average, S.SD, Final, below, above and E.P.C values respectively. The E.P.C values were generated twenty times. The twenty E.P.C values was used to create a database which was used to generate a scatter plot.

Data Analysis of the Simulation Parameters

The values of the clay/shale thicknesses at various depths from the different boreholes were used to model the effective permeability distribution using Monte Carlo Simulation.

The total magnetic intensities were used to generate the lineament orientations of the study area using Geosoft Oasis Montaj and Google Earth.

The relationship between lineament orientations and effective permeability values was used to predict the geotechnical/hazard vulnerability information in Benin City and environs.

Borehole Analysis and Result

Six horizons of four correlatable sand and gravel layers within which were impregnated layers of discontinuous clay/shale lenses at various depths were identified along the forty five boreholes. These horizons are cross sections randomly chosen in such a way that they give an approximate representation of the study area. These horizons are represented as panel diagrams showing the insitu lithology sets with their respective thicknesses. The thicknesses of the clay/shale lenses varied along the horizons. The horizons are labelled as follows: A-A1, B-B1, C-C1, D-D1, E-E1 and F-F1,
where:

- A-A1 passes through seven wells namely; wells 32, 31, 30, 6, 2, 16 & 23.
- B-B1 passes through four wells namely; wells 33, 41, 22 and 24.
- C-C1 passes through seven wells namely; wells 26, 27, 28, 29,15, 5 and 12.
- D-D1 passes through five wells namely; wells 8, 7, 2, 17 and 24.
- E-E1 passes through three wells namely; wells 44, 14 and 39.
- F-F1 passes through three wells namely; wells 45, 38 and 37.

The thicknesses of the shale/clay lenses along the horizons are given below.

1. A-A1 = 2, 4, 8 , 10, 8, 10, 12, 14, 8, 2, 32, 31, 30, 6, 2, 16, 23, 20, 8, 2, 0, 2, 2, 2, 6, 10, 18, 20, 24 m.
2. B-B1= 24, 23, 10, 2, 8, 10, 10, 8, 6, 33, 41, 41, 22, 24, 10, 8, 4, 2, 0 m.
3. C-C1 = 8,6,4, 2, 10,8, 2, 26, 27, 28, 29, 15, 5,12, 0 m.
4. D-D1 = 5, 8, 4, 10, 8, 8, 2, 5, 8, 7, 2, 17, 24, 4, 10, 24, 10, 4, 2, 3, 1, 2, 4, 6, 4, 2, 4, 6, 8, 20 m.
5. E-E1 = 20, 18, 18, 16, 5, 44, 14, 39, 20, 18, 10, 8, 2, 0,2,4, 6 m.
6. F-F1 = 24, 23, 45, 38, 37, 0 m.

The above thicknesses of shale/clay lenses were taken along the horizons expressed in the panel diagrams (Fig. 5). These values are limited to the horizons. In order to account for shale/clay lenses that were not covered and those beyond the horizons, the above thicknesses were subjected to numerical simulation known as Monte Carlo Simulation.

The thicknesses of shale/clay lenses were subjected to twenty eight thousand simulations. These simulations gave the probable thicknesses of the shale/clay lenses along and close to each horizons. Hence, the probable thicknesses of shale/clay lenses of the entire study area is generated. The results of the Monte Carlo Simulations along A-A' section are given in Table 1. This process was repeated for each of the representative horizons.

Table 1: Monte Carlo Simulation along A-A1

AN	AO	AP	AQ	AR
A to A1				
S. Thickness	Smax	Smin	S.average	Final
32	50	7	33.5721	13
33	42	0	25.1593	3
34	60	27	47.5441	53
35	74	29	54.8447	47
36	75	32	50.017	47
35	53	7	32.013	53
36	88	21	47.6263	77
35	67	20	42.0852	63
34	50	10	29.3617	13
35	49	20	34.7685	21
34	34	-14	4.57014	7
35	104	29	67.8407	89
34	42	-2	21.005	11
33	73	18	40.4158	69
32	43	-24	9.25752	-17
33	50	8	29.2655	31
32	47	9	27.5621	45
33	46	2	21.5561	27
34	70	20	49.9609	63
33	43	7	25.4399	39
32	60	5	27.7365	55
31	49	12	29.9509	41
30	32	-38	-11.7665	-33
29	79	7	38.8347	75
30	43	16	31.8106	17
31	55	24	40.7725	41
32	68	23	49.0912	55
33	34	-23	1.69238	-15
34				
33			below	3
32			above	25
31			E.P.C	12

Aeromagnetic Data Processing

Aeromagnetic data for Benin City was obtained from Nigerian Geological and Survey Agency. The data in MS Excel csv format was processed using Geosoft

Oasis Montaj software. The processes include the following:

Gridding

Gridding was performed in order to reveal the Total Magnetic Intensity of the study area with respect to the horizontal(x) and vertical(y) axes. This shows the magnetic anomaly distribution over the study area. The subsurface geology is responsible for the magnetic anomaly. The gridded map showing the total magnetic intensity is shown in Fig. 7.

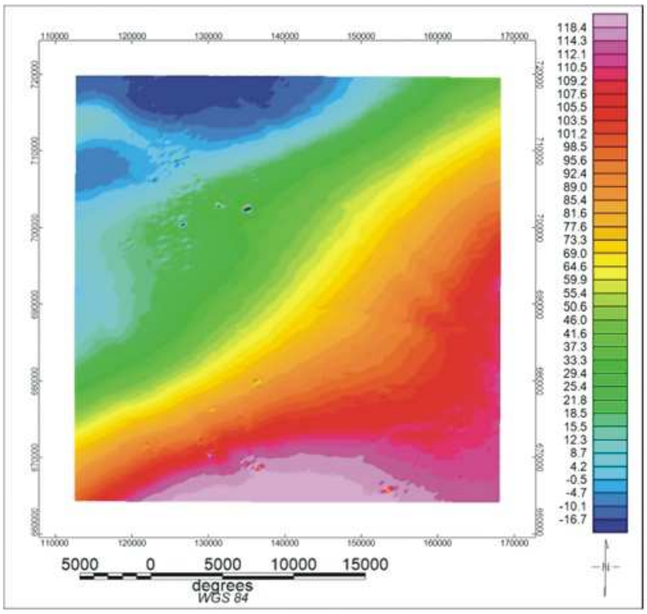

Fig. 7: Map of the study area showing the Total Magnetic Intensity.

Reduction to Equator

The orientation of the magnetic intensity of the earth differs from that of the true magnetic intensity by an amount called Dip. The essence of the reduction to equator is to remove this dip and hence rightly align the earth's magnetic intensity/anomalies over their causative bodies. The study area lies close to the equator and hence reduction to equator is done. If the study area lies close to the pole, a reduction to pole would be recommended. It also reduces the effect of the regional magnetic field of the earth over the local magnetic field due to the causative bodies. Fig. 8 shows the TMI, reduced to the equator.

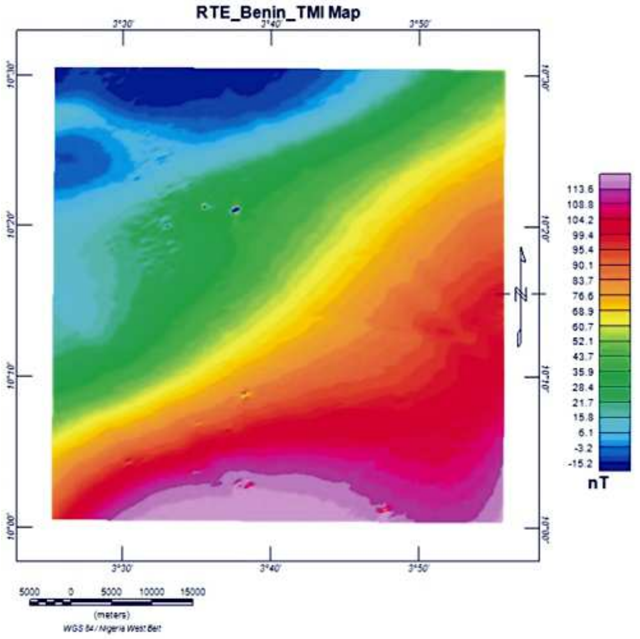

Fig. 8: Map of the study area showing the reduction to Equator of the Total Magnetic Intensity.

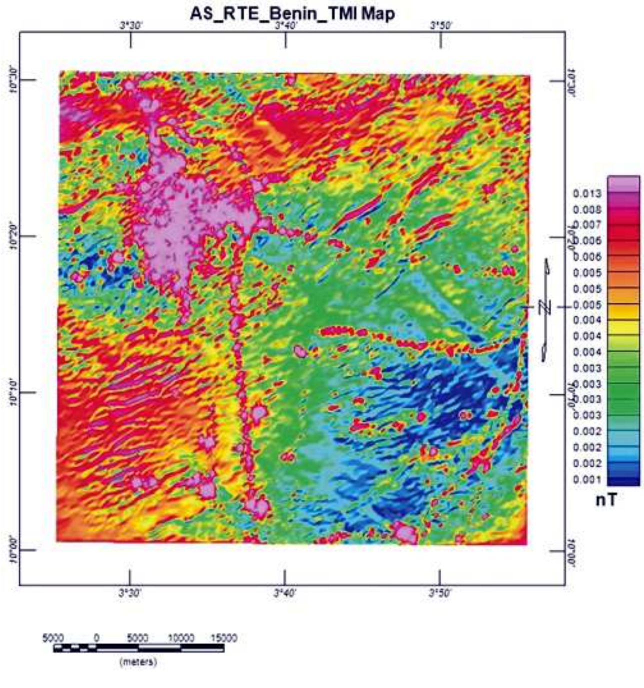

Fig. 9: Map of the study area showing the Analytical processing result of the Total Magnetic Intensity.

Analytical Signal Processing

This is a filtering process that helps to increase the signal to noise ratio of the magnetic intensity. It reduces the effect of the regional effect over the local field. See Fig. 9.

Standard Deviation Generation

This process helps to express the variation of the total magnetic intensity over the study area. This is represented in Fig. 10.

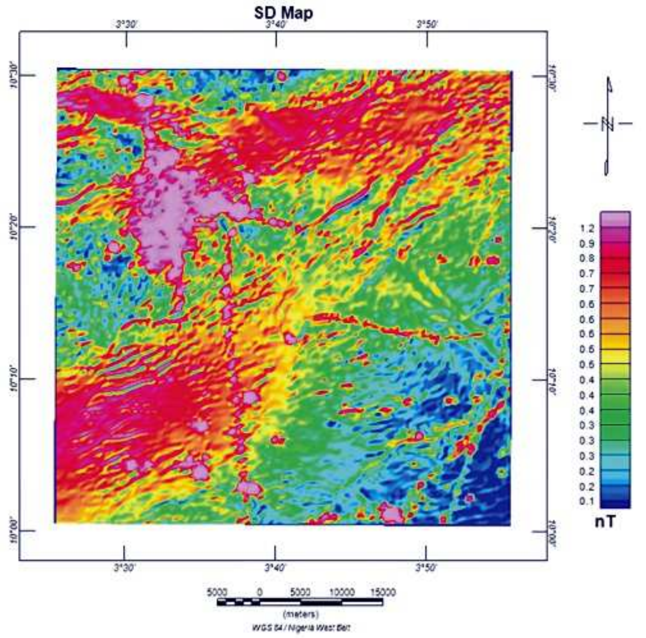

Fig. 10: Map of the study area showing the Standard Deviation result of the Total Magnetic Intensity.

Phase Symmetry Processing

This is a filtering process. It helps to remove the magnetic anomalies due to shallow bodies, leaving behind the anomalies of deep seated bodies. The result is shown in Fig. 11.

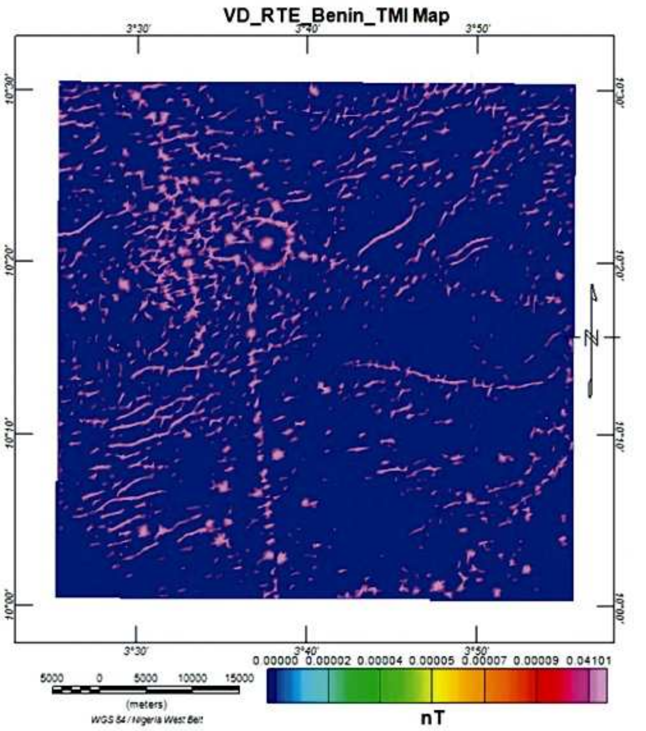

Fig. 11: Map of the study area showing the Phase symmetry result of the Total Magnetic Intensity.

Skeletonisaton of Phase Symmetry

This is a filtering process. This further reduces the effect of the magnetic anomalies due to shallow bodies, leaving behind those due to deeper bodies. This is shown in Fig. 12.

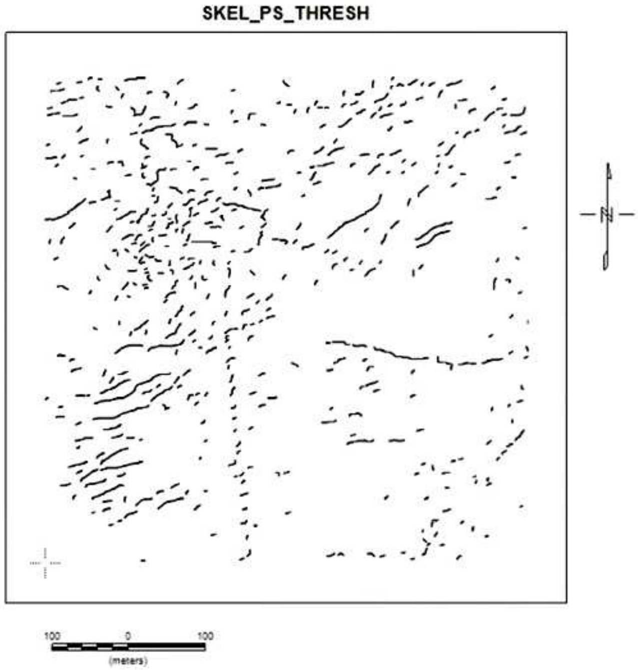

Fig. 12: Map of the study area showing the Skeletonization of the Phase symmetry of the Total Magnetic Intensity.

Vectorisation of Skeletonization Result

This is a filtering process. This reveals the orientation and dimension of the deeper bodies or structure. This exposes the lineament trend of the study area. The lineaments could be faults, joints and so on. The result of this process is shown in Fig. 13.

Integration of Shale Simulation and Trending Lineament

The Effective Permeability Coefficient (E.P.C) obtained via Monte Carlo Simulations were compared with the trending lineament. References were also made to the Aquifer's Transmissivity and Depth to Aquifer's body of the study area. See result in Figure 14.

A scatter plots of twenty effective permeability coefficient (E.P.C) outcomes along the six horizons is the probabilistic effective permeability. This represents a measure of the changing geology of the study area in

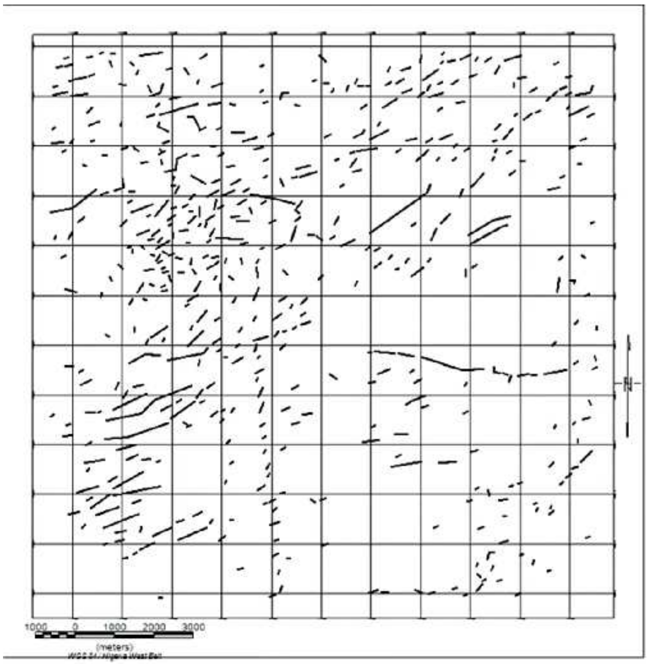

Fig. 13: Trending Lineament Result.

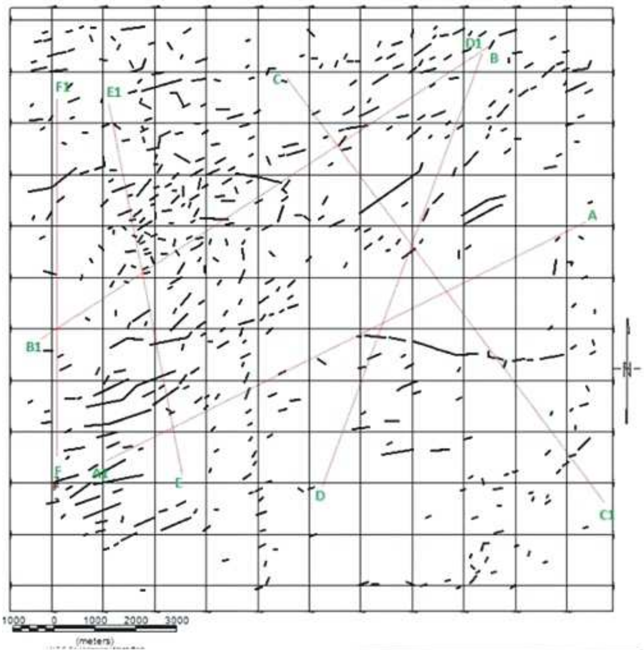

Fig. 14: Map showing Superposition of the Line of Sections over the Trending Lineament.

terms of thicknesses of shale/clay lenses. High values show stable areas while low values show weak areas. The plot is shown in Fig. 15.

Placing the six horizon over the lineament map reveals some interesting features. Areas with homogenous lineament trend tend to have high effective permeability coefficient (E.P.C) values. These areas show unstable zones with high transmissivity and hydraulic conductivities. Areas with complex lineament trends tend to have low E.P.C values. These areas show unstable zone with relatively low transmissivity and hydraulic conductivities. Table 2 shows the effective permeability coefficient data for the study area. Fig. 16 shows the effective permeability coefficient: simulation model of the study area. Fig. 17 presents the environmental hazard vulnerability map of the study area (Benin City.).

Table 2: Effective permeability coefficient data for the study area

A	B	C	D	E	F	G
Simulation	F to F1	E to E 1	D to D 1	C to C1	B to B 1	A to A1
1	12	64.7	27.3	47.4	100	27.3
2	4	55.6	40	40	100	21.7
3	17.4	64.7	27.3	16.7	100	16.7
4	8	47.4	75	27.3	100	7.7
5	7.7	27.3	47.4	21.7	100	7.7
6	12.5	55.6	27.3	16.7	100	12
7	3.7	21.7	27.3	27.3	100	27.3
8	7.7	47.4	47.4	21.7	100	27.3
9	0	33.3	27.3	21.7	100	3.7
10	0	7.7	27.3	64.7	-	3.7
11	12	47.4	40	27.3	100	12
12	7.7	21.7	47.4	47.4	100	7.7
13	12	21.7	21.7	12	100	16.7
14	3.7	40	33.3	21.7	100	21.7
15	7.7	27.3	47.4	21.3	100	7.7
16	12.5	33.3	33.3	27.3	100	27.3
17	17.4	33.3	33.3	33.3	100	12
18	3.7	21.7	47.4	40	100	12
19	7.7	55.6	47.4	16.7	100	16.7
20	12	33.3	33.3	3.7	100	27.3

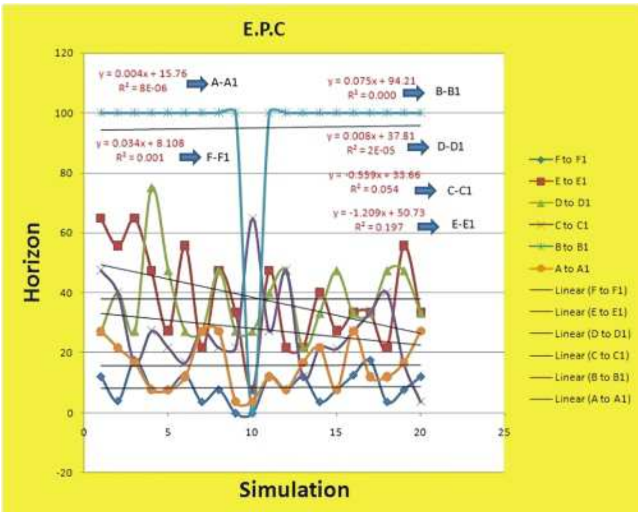

Fig. 15: The effective permeability coefficient simulation Model of the study area.

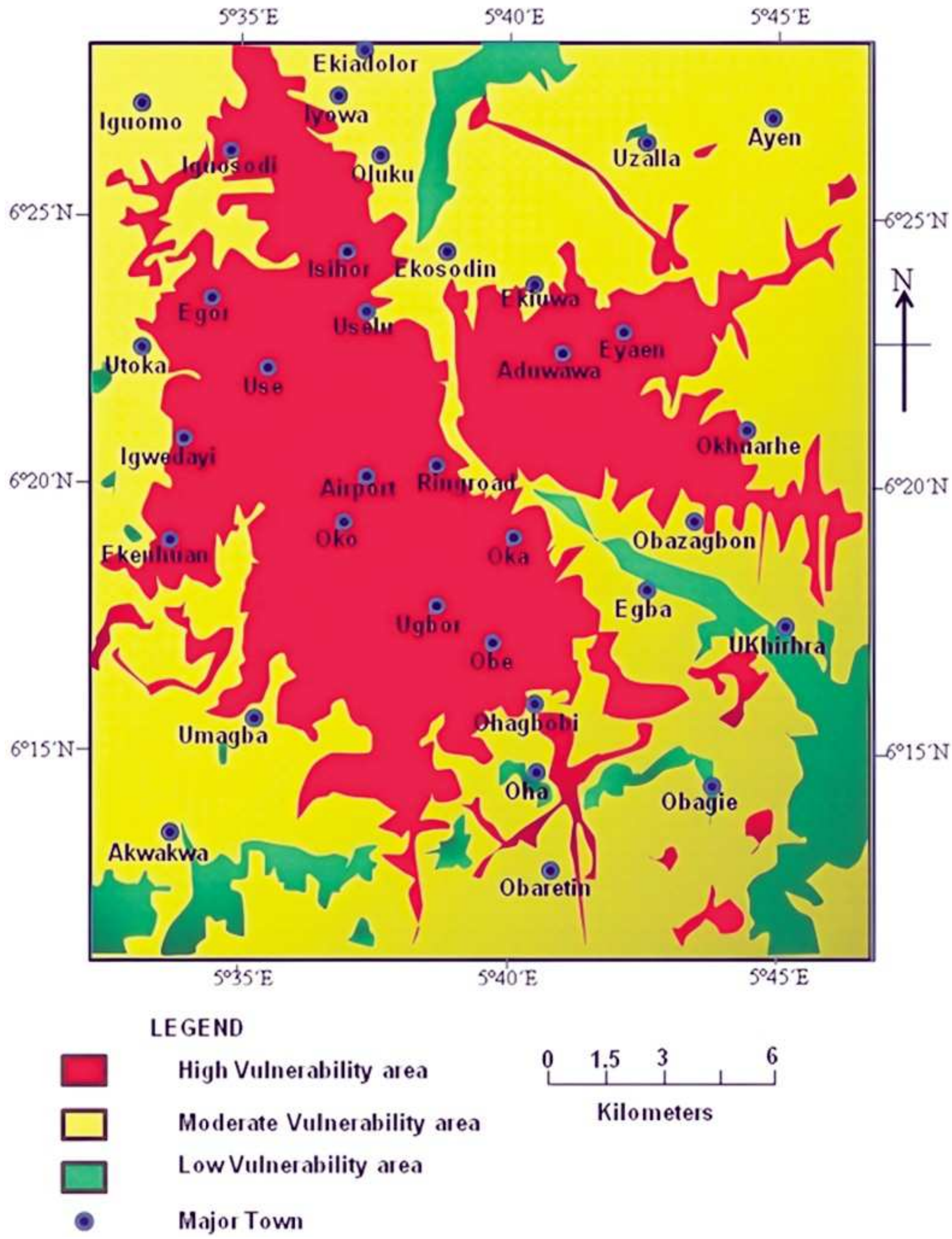

Fig. 17: Environmental Hazard Vulnerability Map of Benin City.

The degree of environmental hazard vulnerability of the study area is shown in the above model. The areas shaded red is most vulnerable, while the yellow coloured areas are the areas that are moderately vulnerable while the green areas are least vulnerable or most stable. This shows that the central part of the study area is highly vulnerable to environmental hazard such as flooding and contamination due to a weak geologic formation, while most areas surrounding the centre and to the outskirts of the city are moderately vulnerable. Also only small and isolated pockets of the area are underlain by stable formation. While the flood prone areas represent areas of most prone to contamination, the stable areas are less prone to contamination by anthropogenic activities in the area.

Discussion

In this chapter, we delve into the implications of our study on the hydrogeological properties of the Benin Formation. By examining relevant literature and employing specific methodologies, we shed light on critical aspects of groundwater dynamics and environmental vulnerability. The present investigation builds upon existing research, emphasizing the following key concepts: Benin City is underlain by the Benin Formation which is comprises fine to coarse sans, clay, shales, gravelly sands. The aquifer occurs at depth range of 31.7 to 55.2 m. The transmissivity and hydraulic conductivity are 1902.2 m per day and 54.4 m per day respectively. The deduction from the geological and hydrogeological characteristics follows the study by previous workers in the Benin Formation. Akujieze and Oteze (2007) studied on the Benin Formation aquifer, estimating it aquifer's yields and transmissivity values. They also delineated the aquifer type. Offodile (2002) concluded that the Benin Formation aquifer is be very thick, extensive and unusually very permeable using lithology logs and pumping test data from the formation. The transmissivity values, storage coefficient and porosity were also estimated. Alile et al (2012) stated the major aquifer in the Ikpoba Okha area to be sand of vary depths. Effective Permeability Coefficient Model: Previous studies have explored the permeability models in various geological formations. Our work contributes by focusing specifically on the Benin Formation. By utilizing data from boreholes and employing Monte Carlo simulation, we enhance our understanding of groundwater flow and transport within this region.

Application of Monte Carlo Method for Effective Permeability Modeling followed the work of past workers. Notably, Zheng et al., (2022) proposed a Monte Carlo algorithm to estimate the relative permeability of mixed-matrix membranes (MMMs). By adjusting diffusivity coefficients and solubility at the polymer-filler interface, they accurately predicted permeability. This method can be extended to non-ideal MMMs and various filler geometries. Also, numerical method has been used by different researchers to characterize different lithologies and estimate permeability. Dmitry et al (2010) calculated effective permeability numerically using Double Randomization Monte Carlo Simulation.

Lineament Analysis: Lineaments, indicative of subsurface fractures and faults, have been extensively studied in hydrogeology. Our aeromagnetic analysis allowed us to extract lineament trends and density, providing valuable insights into the structural characteristics of the study area.

Based on the method applied for the study, six representative horizons (A-A1, B-B1, C-C1, D-D1, E-E1, and F-F1) across the 45 wells. These horizons serve as reference points for assessing various parameters, including thickness and final values. This is in line with the work of Prabu and Rajagopal (2013) who demonstrated a close relationship between lineaments and groundwater flow and yield. Lineaments often indicate zones of localized weathering and increased permeability, making them crucial for groundwater exploration and management. The effective permeability coefficient model for the study area was derived from borehole data, quantifies the permeability of the Benin Formation. This information is crucial for sustainable groundwater management and resource utilization.

Omowumi (2022) discussed the application of geophysical investigation for structural studies. The stability/vulnerability in the face of diverse environmental conditions therefore vary. Vulnerability to hazards of a near surface is closely related to the relative stability or otherwise of the underlying subsurface structure. Geophysical and hydrogeological methods have been used by different researchers to define the thicknesses, shapes, horizons and subsurface layers in both crystalline and sedimentary terrains. Longe et al (1987) used well logs, pumping test data, borehole yields and water quality data in Lagos Metropolis to define the Metropolis's aquifer types with their average corresponding transmissivities. Asiwaju-Bello and Oladeji (2001) produced the hydrostratigraphic model of Lagos Metropolis using geologic well logs, pumping test data and static water level and the model delineated the aquifer type to three with varying hydrogeological properties.

The first result of the analysis of the aeromagnetic data yielded a total magnetic intensity map. Further refinement improved signal-to-noise ratios. Further refinement, resulting in derivation of the standard deviation and phase symmetry maps. The phase map, after skeletonization and vectorization, revealed the desired lineament characterization of the area. Lineament Trends: Detailed analysis centered around the exploration targeting (CET) grid revealed predominant north-east lineament orientations, with localized north-west and north trends. The central study area exhibits high lineament concentration, while peripheral regions show lower concentrations. Application of Lineaments in Geological Characteristics was previously captured in the work of Akinluyi et al., (2018) investigated the influence of lineaments on groundwater flow in basement complex and established that the lineament structures offer a structural control to the groundwater flow in basement areas. They concluded that areas with more lineaments yielded more water than areas with less lineaments. Similarly, Ceccato et al., (2022) investigated the multiscale analysis of lineament patterns in fractured crystalline basement blocks. They highlighted the hierarchical structure of fracture networks and their impact on permeability prediction. Integrating field petrophysical analyses of fracture lineaments improved the accuracy of permeability estimates. Similarly, the findings of this research, when combined with field data, enhance the accuracy of permeability estimates in the Benin Formation, hence the mapping of hazard vulnerability.

Hazard Vulnerability Mapping, by integrating lineament and permeability datasets, a hazard vulnerability maps was created for Benin City and its surroundings. This map highlights areas prone to erosion and flooding, aiding urban planning and disaster preparedness. The environmental implications of the findings underscore the environmental challenges faced by Benin City such as flooding and contamination risk. The weak geologic formation in the central study area renders it highly susceptible to flooding. Urban planners must consider this vulnerability when designing infrastructure and flood control measures.

Finally, the current study bridges theory and practice, providing actionable insights for sustainable water resource management and potential areas as targets for hazard mitigation planning and environmental management in the Benin City and the environs.

Conclusion

In this study, the geological and geotechnical characteristics of the Benin Formation were investigated to characterize the area in terms of the hazard vulnerability based on the lineament and effective permeability studies. Our findings reveal the following key points:

Benin City is underlain by the Benin Formation which is comprises fine to coarse sans, clay, shales, gravelly sands. The aquifer occurs at depth range of 31.7 to 55.2 m. The transmissivity and hydraulic conductivity are 1902.2 m per day and 54.4 m per day respectively. A set of simulation parameters was defined to compartmentalize the subsurface into horizons based on defining lithological characteristics. Six representative horizons (A-A1, B-B1, C-C1, D-D1, E-E1, and F-F1) were defined across the 45 wells. Parameters such as thickness, maximum and minimum values (Smax, Smin), average (S.average), standard deviation (S.SD), and final values were established.

Using the Monte Carlos simulation, the effective permeability coefficient Model was generated for the entire study area using these data from 45 boreholes. From the lineament analysis, the lineament characteristics (trend and density) model was extracted from the aeromagnetic data. Hazard Vulnerability Mapping by the integration of both the lineament characteristics and effective permeability datasets, yielded a hazard vulnerability map for Benin City and its environs. Detailed analysis of lineament trends using the Centre for Exploration Targeting (CET) Grid revealed a predominant north-east orientation, with pockets of north-west and north orientations. This map highlights areas susceptible to erosion and flooding based on the stability or weakness tied to the lineament characteristics. The central part of the study area exhibits a high lineament concentration, hence higher hazard vulnerability, while the periphery areas have lower concentrations or less hazard vulnerability.

Indeed, our study provides valuable insights into the hydrogeological, geological and geotechnical properties of the Benin Formation, aiding in mapping the hazard vulnerability of the area.

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Conflict of Interest

There is no conflict of interest.

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