Modelling Surface Runoff and Mapping Flood Vulnerability of Lagos State from Digital Elevation Model

Olayemi Joseph ODUMOSU, Oluibukun Gbenga AJAYI and Ekundayo ADESINA, Nigeria

Key words: Flooding, Digital Elevation Model, hydrology, Coastal State

SUMMARY

This Paper presents a new approach to flood mapping via Digital Elevation Model (DEM). The DEM of the study area was downloaded from the USGS Website after which the Water Shed, drainage basin, flow direction, water channels, channel network, accumulation flow and flow length were modeled using quantum GIS. Pit removal was performed using parallel computing method and the D-Infinity algorithm was utilized in computing flow direction.

Thereafter, arbitrary gauge stations were set up at Eleven (11) points across the study area and a run-off simulation was done at One hourly (1 Hr) Interval for an Eight hours Homogenous rainfall.

The gauges with high guage readings at the end of the simulation period were then considered to be areas with high runoff, hence, flooded.

A flood vulnerability map of Lagos State is then prepared based on both the flow accumulation maps and the gauge readings.

The Model proved optimal as it produced result in accordance with real situations within the study state.

Modelling Surface Runoff and Mapping Flood Vulnerability of Lagos State from Digital Elevation Model

Olayemi Joseph ODUMOSU, Oluibukun Gbenga AJAYI and Ekundayo ADESINA, Nigeria

ABSTRACT

Flooding in recent times has become a critically problematic phenomenon of spatio-temporal order and considerably high frequency of occurrence all over the world and most especially in coastal nations / states. Lagos State, one of the nine (9) Coastal States of Nigeria has witnessed and is still witnessing multivariate cases of flooding which attains it's peak in the rainy seasons (April-October) of every year resulting to loss of life and economic valuables/properties. In order to curb this menace, an integrated solution (combination of empirical hydrological models with remote sensing and GIS capacity) is thus herein presented using a downloaded Digital Elevation Model of the study area to delineate water shed, flow direction, contributing areas and flow path/Channel. Also, surface runoff was simulated for an eight hours homogenous rainfall and the resulting gauge readings from eleven (11) fictitious gauge station distributed across the state was obtained. The study was able to produce a map categorising Lagos state into three (3) zones on the basis of their vulnerability to flood. The Quantum GIS software was used for the analysis and simulation.

1.0 INTRODUCTION

As a consequence of global warming; sea level rise, climate change and several other related factors, probability of inundation in the floodplains and river catchment areas has recorded significant increase which in turn has resulted into incessant increase in flooding occurrences. **F**looding in recent times has become a critically problematic phenomenon of spatio-temporal order and considerably high frequency of occurrence especially in coastal nations / states. It therefore becomes necessary to effectively estimate and forecast flooding so as to prevent its ill-effects.

On a small area basis, fully empirical solutions could suffice, however as extent coverage increases and consequently drain network becomes more complex, deterministic and reservoir runoff models with graphical capability becomes the best approach. This makes the use of GIS for flood monitoring and control a very efficient tool.

As remote sensing precisions and accuracies have improved over the years, Digital Elevation Models (DEMs) have gone from 30 – 100 meter resolution to 1 – 5 meter resolution presently for most part of the Earth's Land Surface (Wallis et al, 2009). Besides, the global-extent coverage and easy on-line accessibility of high precision DEM's are beginning to give its use great relevance in large scale regional projects and researches. Terrain analysis based on digital elevation models are therefore being increasingly used in hydrology (e.g Wilson and Gallant, 2000). Detailed Land Surface Topography is used in Hydrology for a number of purposes, including analysis and prediction of soil moisture based on specific catchment area and wetness index (Borga, M et al, 2002), development of flow model, mapping channel network of streams path amongst others.

Generally, developing a flow model and mapping the channel network from a gridded Digital Elevation Model follows a now-well- rehearsed procedure (Wallis et al 2009) of (1) filling Sinks (2) Computing Flow Directions (3) Computing the contributing area draining into each grid cell.

In this paper, hydrological information derived from a DEM of Lagos state, Nigeria was used to model the surface run-off and to produce a flood vulnerability map of the Study Area (Lagos State Nigeria). The Quantum GIS software and its associated hydrology plugins were used in the course of this research.

2.0 LITERATURE REVIEW:

Though several research attempts (using basically stochastic and deterministic hydrological models as well as empirical, reservoir runoff model e.t.c) have been made to ameliorate the problem of flooding, recent research in hydrologic modelling attempts to propose a more global approach to the understanding of the behaviour of hydrologic systems to make better predictions and to face the major challenges in water resources management.

Soojeong, M et al (2009) identified all major factors responsible for flooding and used the AHP method to develop and impose weights for each factor. The weighted factors were then modelled together using ArcGIS to produce a flood vulnerability map for North Korea. Other GIS based flood modelling techniques include TauDEM (David G Tarboton, 2006), Real Time Flood emergency mapping e.t.c

David, R. M (1996) gave a general 10-step modelling process for surface hydrological mapping which include (1) Study Design (2) Terrain Analysis (3) Land Surface (4) Sub-surface (5) Hydrological Data (6) Soil Water balance (7) Water Flow (8) Constituent transport (9) Impact of Water utilisation (10) Presentation of results

3.0 DESCRIPTION OF PROCESS:

The practical steps involved in this research are as highlighted and elucidated below:

3.1 Pit Removal: Hydrologic terrain analysis augments the information content of digital elevation data by removing spurious pits, deriving a structured flow field, and calculating surfaces of hydrologic information derived from the flow field (Wallice et al, 2009). Drainage correction is generally the first step in the established procedures for developing a flow model and deriving flow related fields that augment the information content in a DEM (Beven and Moore, 1992; Wilson and Gallant, 2000; Tarboton and Ames, 2001; Maidment, 2002). The most common approach to drainage correction is to fill pits (pit removal). Several algoritms exist for filling pits including pour points method (as used in

ArcMap), Planchon's method (Planchon and Darboux, 2001; Arge et al., 2003), Arge's method (Agre et al, 2003), Pit carving (Garbrecht and Martz, 1997; Soille et al., 2003), etc.

3.2 Computation Of Flow Directions: The most common procedure for routing flow over a terrain surface represented by a grid DEM is the eight direction method (D8) where the direction of steepest descent towards one of the eight (side and diagonal) neighbouring grid cells is used to represent the flow field (O'Callaghan and Mark, 1984). Other methods include the D-infinity multiple flow direction (D∞) (Tarboton, 1997) and Rho 8.

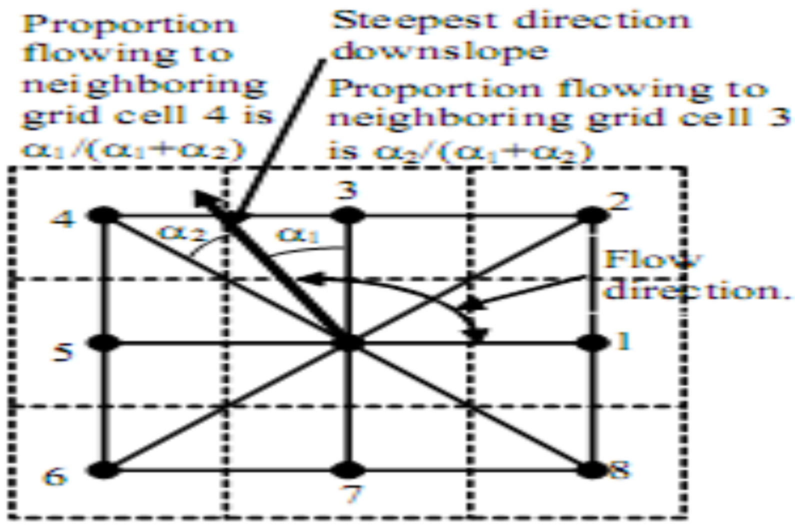


Figure 1: (Diagram by David Tarboton) D-8 multiple flow direction model (Tarboton, 1997). Flow direction defined as steepest downwards slope on planar triangular facets on a block centered grid.

All flow field methods assign flow from each grid cell to one or more of its adjacent neighbours. In grid DEMs the basic model element is a grid cell, but the same concepts can be applied to any set of topologically connected model elements. The flow proportions assigned to each downslope element are positive and should satisfy the conservation constraint viz:

$$\sum_j P_{ij} = 1 \qquad \text{Equ 1.}$$

A major advantage of the Quantum GIS software is its capacity to allow users to specify the precise algorithm of choice and also make comparative choice of the best amidst such models.

3.3 Compute Contributing Area: Once the flow direction has been computed, the next task is to evaluate contributing area and other accumulation derivatives across the DEM domain. Thus the general accumulation function for each grid is defined as the integration of a loading field over a contributing area:

$A = \int_{CA} w.\, da$ Equ 2.

Mark (1988) presented a recursive algorithm for evaluation of accumulation in the D8 case that was extended to multiple flow direction methods by Tarboton (1997). Numerically, flow accumulation is evaluated recursively for each element as:

$A_i = w_i \Delta + \sum_{(k:P_{ki}>0)} P_{ki}\, A_k$ Equ 3

Where i is a location in the field, represented numerically by a model element such as grid cell in a DEM and A_i represents the accumulation at that element. The model element area is Δ and the $(k: P_{ki} > 0)$ notation denotes that summation is over the set of k values such that P>0 (i.e., summing the contribution from neighbouring elements k to element i).

Sections 3.1 to 3.3 above give a quick description of the mathematical and logical background of the process involved in modelling channel network and a drainage basin from a DEM. Similarly, a brief illustration on the concept of run-off modelling and simulation is given in the next few sections.

3.4 Surface Runoff: Rainfall runoff relationship can be visualized by some factors such as initial abstraction (Ia), direct runoff (Q), and actual retention (F). The Curve Number (CN) is an index developed by the Natural Resource Conservation Service (NRCS), to represent the potential for storm water runoff within a drainage area. The CN for a drainage basin is estimated using a combination of land use, soil, and antecedent soil moisture condition (AMC). There are four hydrologic soil groups: A, B, C and D. Group A have high infiltration rates and group D have low infiltration rates (Ratika et al, 2010).
The water balance equation is expressed by:

$Q = \frac{(P-Ia)^2}{(P-Ia)+S}$ Equ 4

Where Q = Amount of runoff in mm
P = Rainfall in mm
S = Max amount of Water that will be absorbed after the commencement of runoff in mm
Ia = Initial Abstraction (All loses before runoff commences including water retained in depression, water taken by vegetation, evaporation e.t.c)
$Ia = 0.2 \times S$

Therefore $Q = \frac{(P-0.2S)^2}{(P+0.8S)}$ Equ 5

However, since S is related to Soil and Cover Characteristics, it is thus related to the runoff Curve Number (CN) which is a function of soil type and Land use (Geology of the area).

3.5 Manning's Value: Another important factor to be considered which is often dependent on the study area's geology is the Manning's value of the resulting DEM channel.

$$V = \frac{K}{n} Rh^{2/3} S^{1/2} \qquad \text{Equ 6}$$

Where V = Cross sectional average Velocity (L/T; ft/s, m/s)

K = Conversion Factor of ($L^{1/3}$ / T)

n = Gauckler – Manning coefficient (unitless)

Rh = Hydraulic Radius

S = Slope of the water surface or the linear hydraulic head loss

Chow (1959) published certain standard values of Manning's coefficient or value for closed conduits flowing fully, partially and corrugated metal pipes. The Earth cut natural drain, winding and sluggish manning's value of 0.030 was adopted for this study.

4.0 STUDY AREA

With a land area of about 6500 sq Km, Lagos State is a low-lying coastal state that is bounded in the South by the Atlantic Ocean and the Lagoon. Several other tributaries from the Lagoon extends into the state, some of which includes the five cowries, the Iddo Port, amongst others. Lagos State due to its proximity to the Atlantic Ocean and accessibility to the rain-bearing wind currents often experience several cases of flooding especially during the rainy season between April and October.
Recent coastal deposits occur widely in Lagos State. Also, tertiary beds from the Benin Formation stretch from Calabar in the Far East through Lagos state to the borders of Benin Republic in the west.

The Map of the Study area is as shown in Figure 1 below:

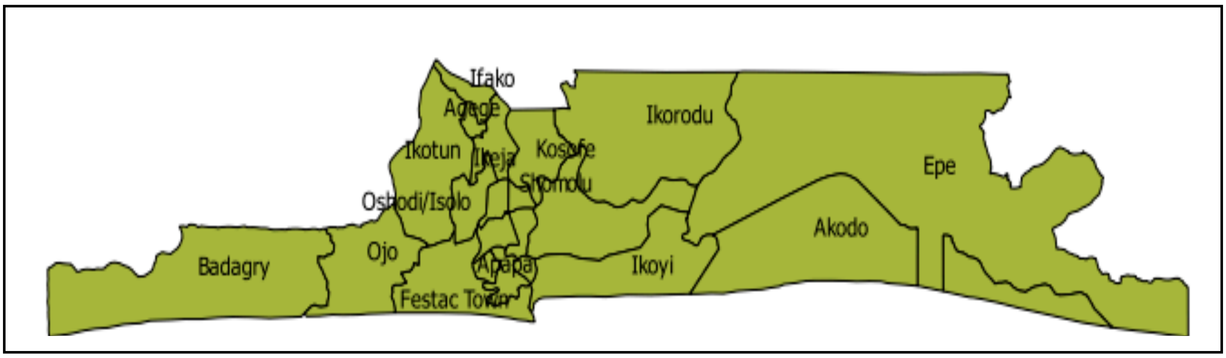
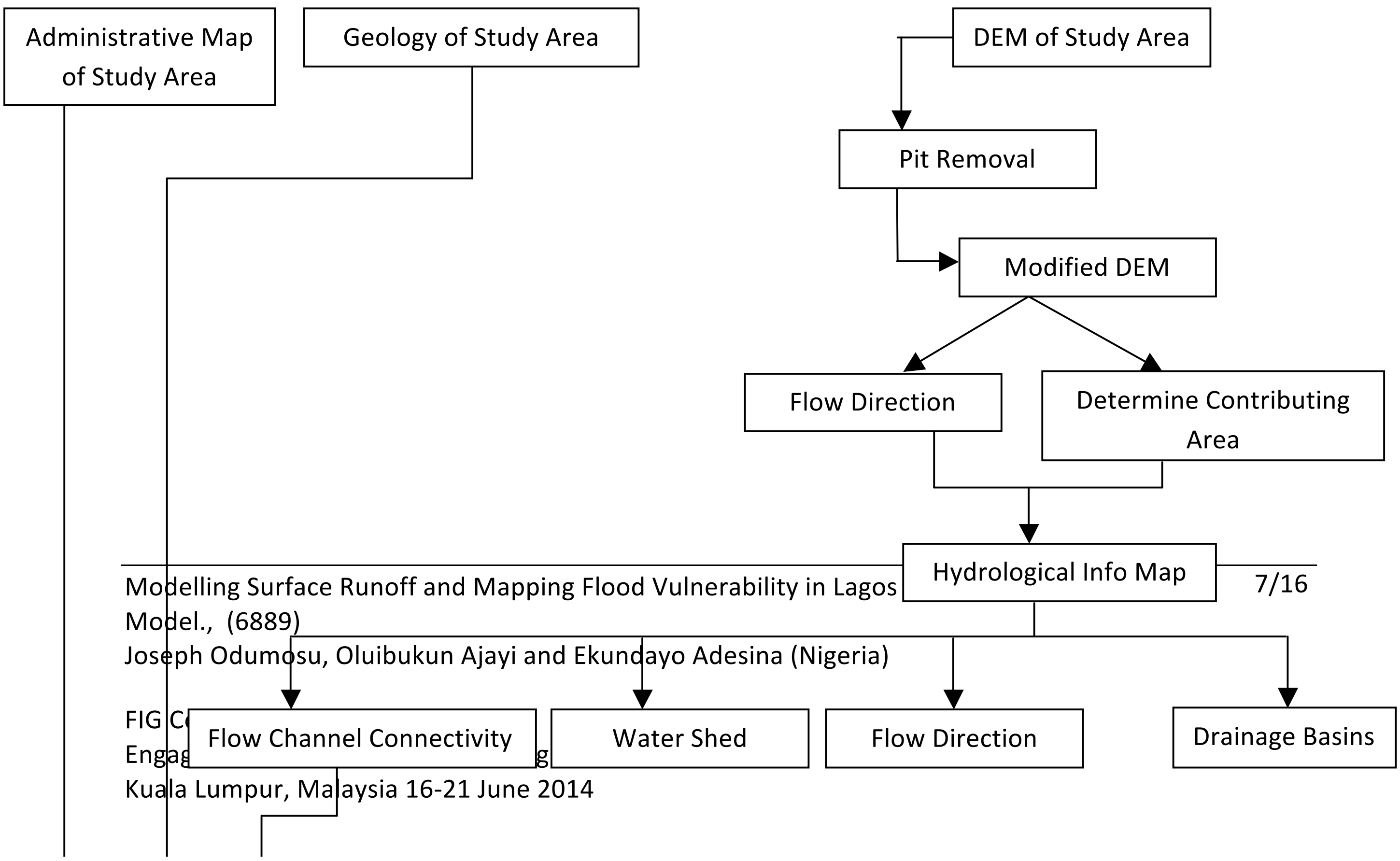


Fig. 1.0: Administrative map of Lagos State. (Source: Authors)

5.0 CONCEPTUAL DESIGN: For quick and concise understanding, the conceptual design and methodological flow for this research is as shown in the flowchart below:



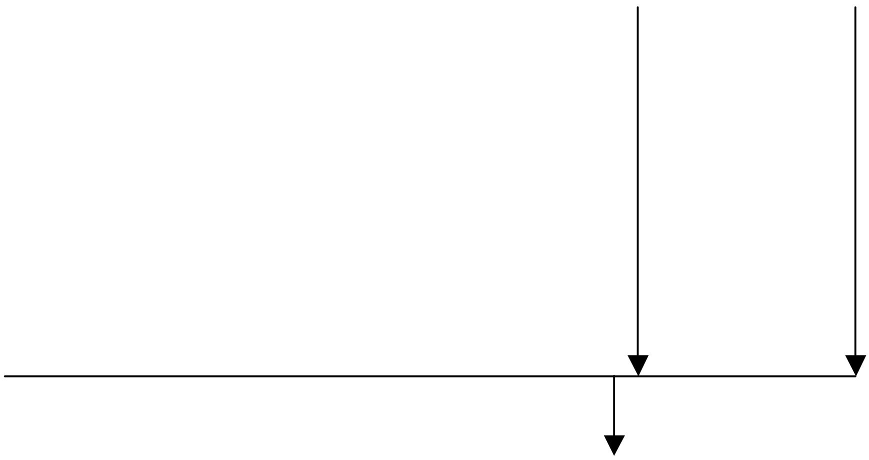


Fig. 2: Flowchart describing the step by step stages of the conceptual design of this work (Source: Authors)

The Digital Elevation Model (obtained from USGS website), Administrative map and certain geological information (Such as Soil Type, Percolation rate of soil, Mannings value, surface roughness e.t.c which were required for empirical computation of runoff) serve as key inputs into the solution Process. Hydrologic terrain analysis is then performed on the DEM to provide key Hydrological information about the study area. This resulting information is thereafter integrated in an empirical solution to determine the surface runoff. The results are graphically presented to show flood vulnerability within the study area.

6.0 RESULTS

The SAGA tool contained within the processing toolbox of QGIS was utilised for this task. SAGA in-built program routines such as the "***Simulations-Hydrology***", "***Terrain Analysis-Channels***" and "***Terrain Analysis-Hydrology***" were used for performing the various operations to obtain the results displayed below.
A major benefit of QGIS – tools is that the program routines are executed via user a friendly interactive window that allows users specify desired computational algorithms amongst the various available options.
The ArcGIS Hydrology toolbox was also used to test the process and similar results obtained within allowable discrepancy (though comparison of results from various software and computational

algorithms is not done as it is not the concern of this paper). Presented below are various maps showing the outputs of the model:

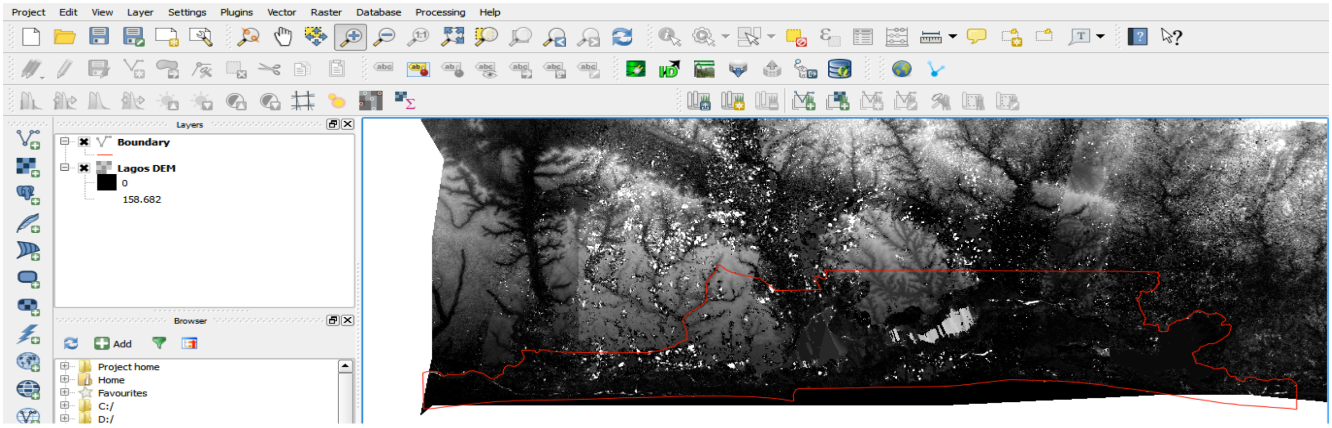


Fig 3: DEM of the Study Area with pits downloaded from USGS website.

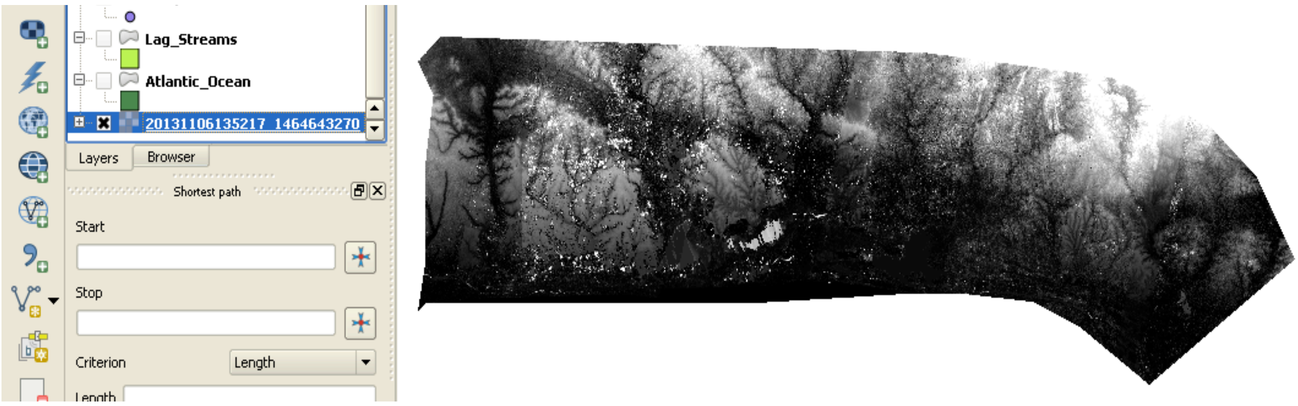


Fig 4: DEM of the Study Area without pits i.e. the Pits have been removed.

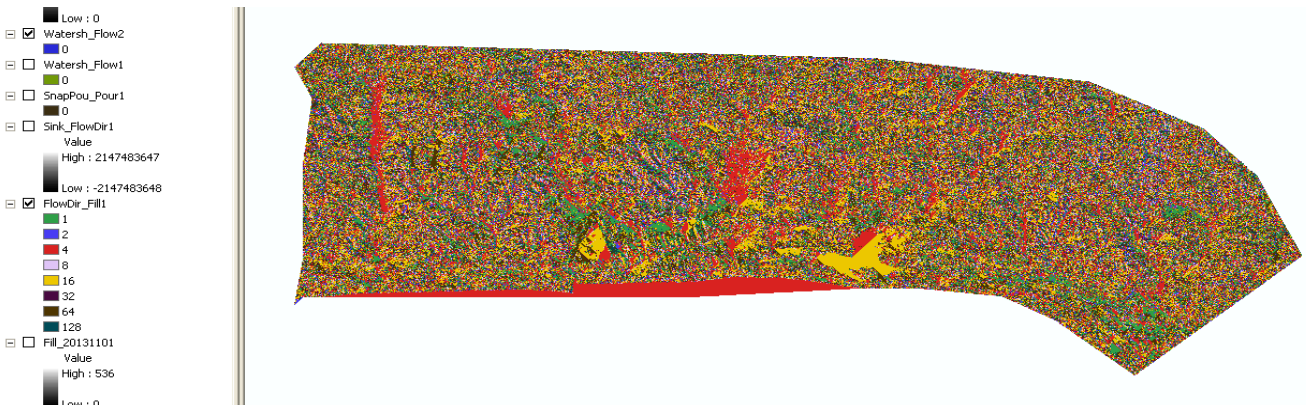


Fig 5: Map showing Flow Directions within the study area produced from QGIS.

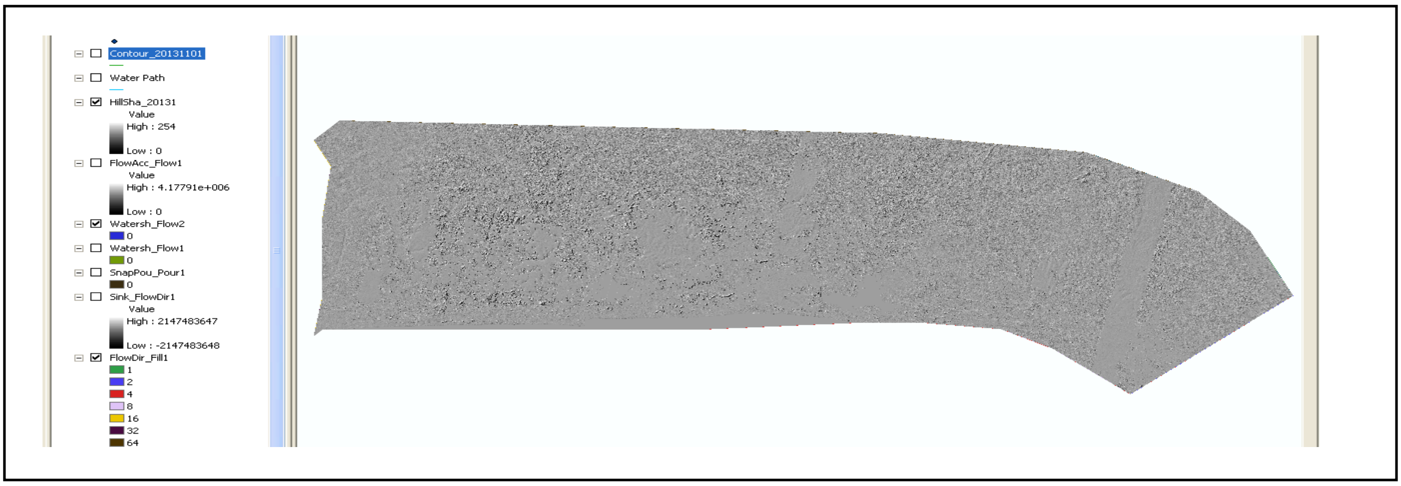


Fig. 6: Slope Map of the study area produced from QGIS.

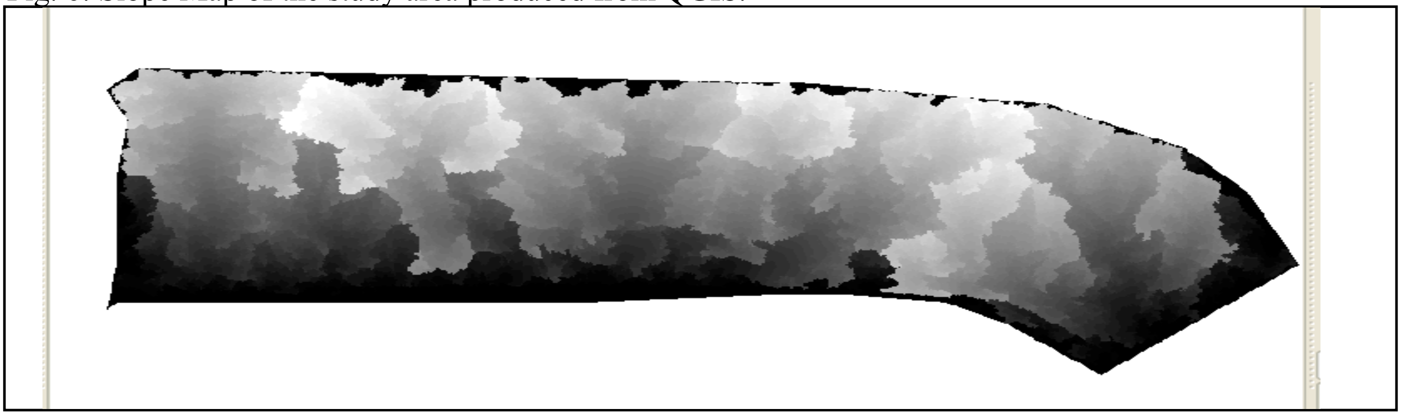


Fig. 7: Map showing the DEM generated Drainage basin

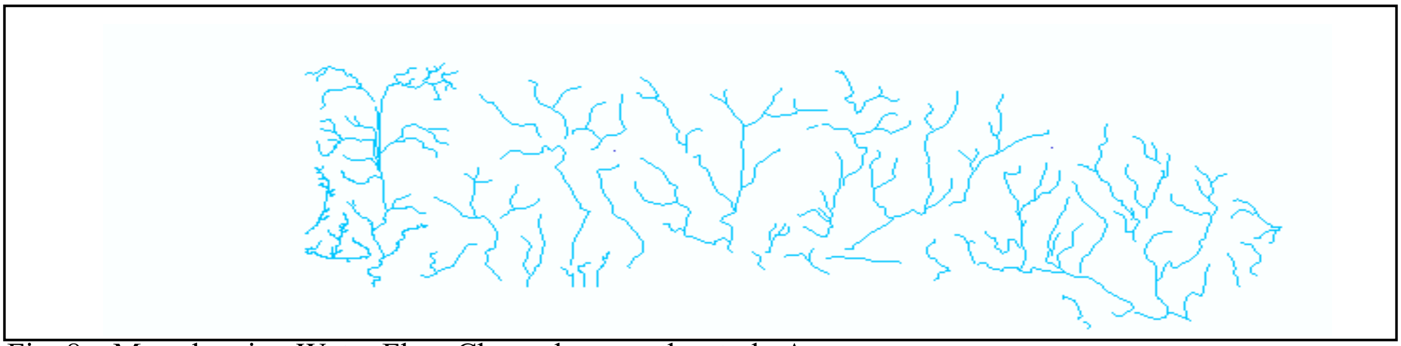


Fig. 8a: Map showing Water Flow Channel across the study Area.

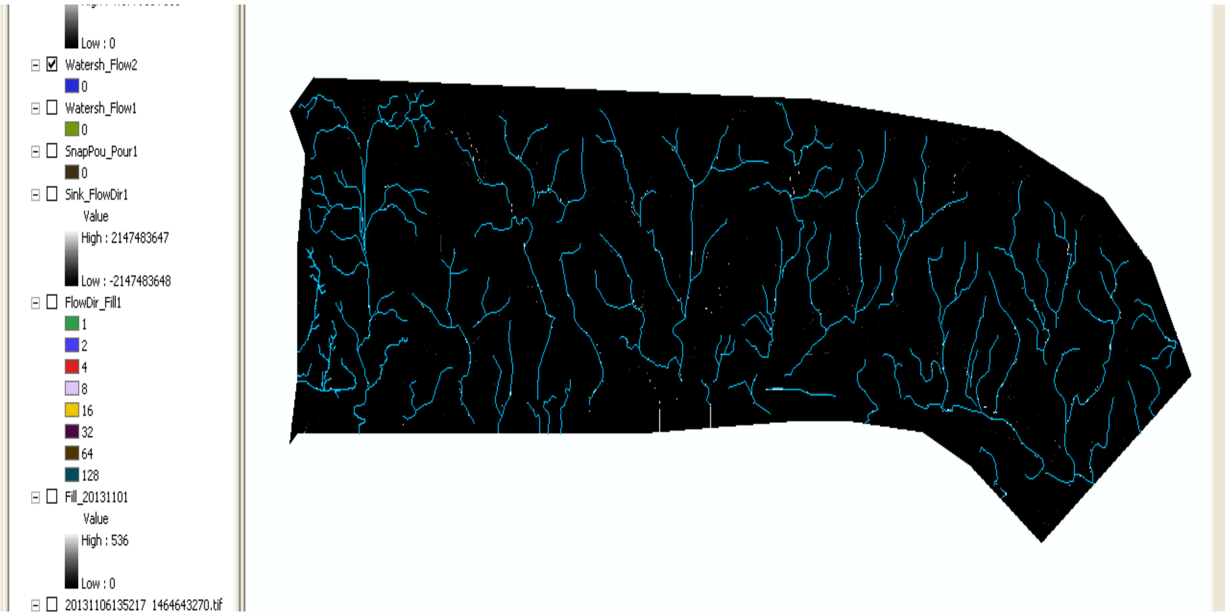


Fig. 8b: Flow Connectivity Network across the study Area.

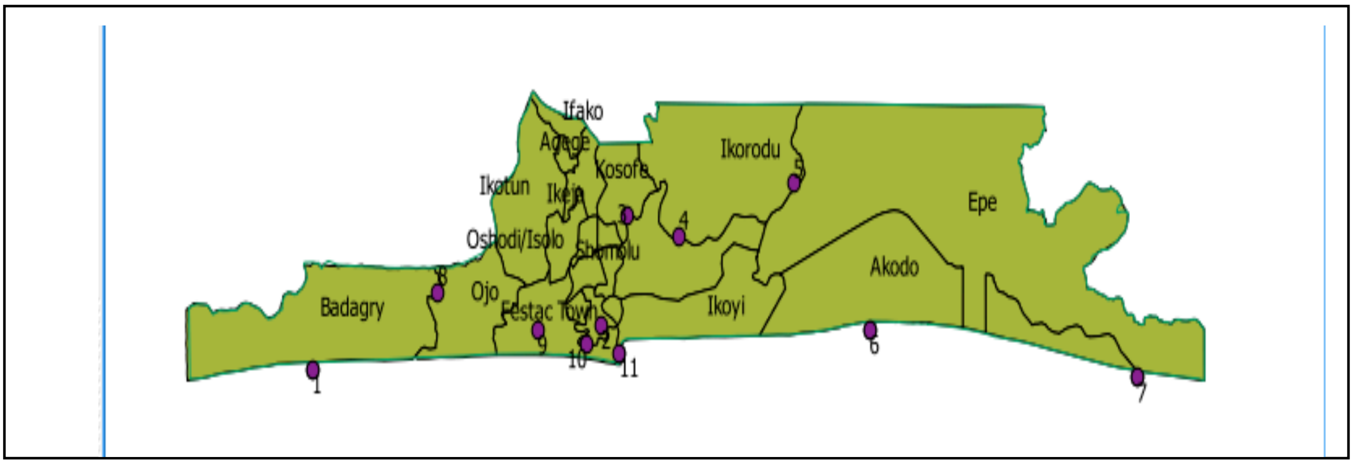


Fig. 9: Pour Points/ fictitious gauge stations set up to measure predicted runoff.

7.0 DISCUSSION OF RESULTS:

Figures 3 and 4 shows the Digital Elevation Model for Lagos State, downloaded from www.usgs.gov. After removing the pits, a D-infinity flow direction was run and the result obtained is presented in Fig. 5. This depicts that the flow direction/Pattern across the state is seemingly from North to South around Badagry Local Government, while it is uniformly distributed in other areas, with Shomolu, some parts of Ajeromi / Ifelodun, Apapa and Kosofe Local governments naturally draining into the Oworonsoki natural drain channel.

The slope map shown in Fig. 6 further substantiates the above claim. The drain basin shown in Fig. 7, gives a first order initial idea of the areas susceptible to flooding within Lagos State. While areas like Kosofe, Some parts of Oshodi/Isolo, Ikorodu, Some areas in Epe and Akodo stand as being above

flood level, others are ranked as either "Closely susceptible" or "Highly susceptible to flooding" respectively.
Finally, eleven (11) fictitious Gauge Stations were set-up across the state and an homogenous rainfall was simulated for 8 hours. Gauge values at 1hour interval were then predicted based on runoff at each of these gauges and they were used for the production of the flood Map of Lagos – State.
It should be noted that these simulations holds sway in consideration of the run-off as a function of rainfall and DEM and under the assumption that all water is free flowing without impedance along drainage paths. Situations of blocked or insufficient drainage are not considered.

See Tables 1 and 2 respectively:

TIME	GAUGE_01	GAUGE_02	GAUGE_03	GAUGE_04	GAUGE_05	GAUGE_06	GAUGE_07	GAUGE_08	GAUGE_09	GAUGE_10	GAUGE_11
8	0	91.046841	325.12591	32.910667	4.973444	0	0	109.395759	20.314612	141.442428	0
7	0	52.704612	331.451983	10.81148	0.227795	0	0	15.832881	6.389083	7.090965	0
6	0	14.086308	159.590624	5.300722	0.029959	0	0	2.669261	0.593326	0.984081	0
5	0	1.873876	81.693579	5.088228	0.007234	0	0	0.437766	0.103866	0.248868	0
4	0	0.392645	74.320323	0.388186	0.002521	0	0	0.116176	0.029772	0.089949	0
3	0	0.122004	41.584158	0.054601	0.00111	0	0	0.043521	0.011733	0.040738	0
2	0	0.049706	8.911019	0.013056	0.000573	0	0	0.020319	0.005675	0.021466	0
1	0	0.024332	2.314943	0.004509	0.00033	0	0	0.010977	0.003149	0.012586	0
0	0	0.013537	0.786156	0.001991	0.000207	0	0	0.006566	0.001925	0.007982	0

Table 1: Results of Simulation of Rainfall for 8 hours

GUAGE NO	LOCATION	REMARKS After 2Hrs	REMARKS After 4Hrs	REMARKS After 6Hrs	REMARKS After 8Hrs	GENERAL REMARKS
GUAGE 1	Badagry	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE
GUAGE 2	Apapa	NOT FLOODED	NOT FLOODED	NOT FLOODED	FLOOD BUILDING	CLOSELY SUSCEPTIBLE
GUAGE 3	Kosofe	NOT FLOODED	FLOOD BUILDING	FLOODED	FLOODED	HIGHLY SUSCEPTIBLE
GUAGE 4	Ikorodu	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE
GUAGE 5	Ikorodu	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE
GUAGE 6	Akodo	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE
GUAGE 7	Epe	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE
GUAGE 8	Ojo	NOT FLOODED	NOT FLOODED	NOT FLOODED	FLOODED	HIGHLY SUSCEPTIBLE
GUAGE 9	Festac Town	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE
GUAGE 10	Apapa	NOT FLOODED	NOT FLOODED	NOT FLOODED	FLOODED	HIGHLY SUSCEPTIBLE
GUAGE 11	Ikoyi	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT FLOODED	NOT SUSCEPTIBLE

Table 2: Flow Analysis

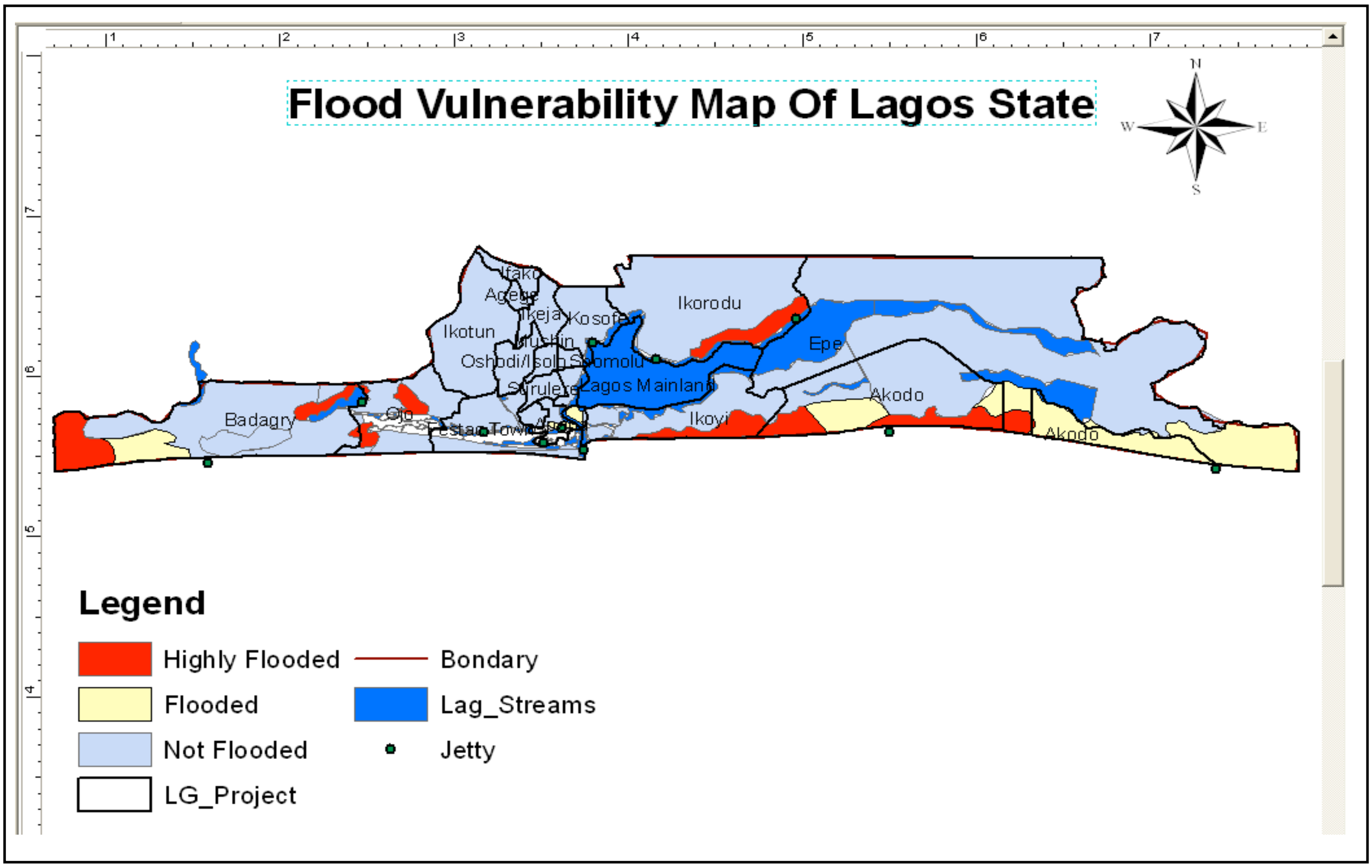


Fig 10: Showing Flood Vulnerability Map based of Lagos State.

8.0 CONCLUSION

This paper has investigated the surface hydrology and flood dynamics of Lagos State via hydrological simulation using the Quantum GIS software. Areas that are not naturally self draining on the basis of relief have been identified as “Highly Susceptible to Flood” and the well drained identified as “Not Flooded”. It has also been discovered that Ikoyi, a high brow area of Lagos and often “flood-Spot” ought not to be flooded if all drainage channels that link it to the Lagoon can be properly widened and cleared at all times.

REFERENCES:

Arge, L., Chase, J., Halpin, P., Toma, L., Vitter. J., Urban. D and Wickremesinghe. R, (2003), "Efficient flow computation on massive grid terrain datasets," *Geoinformatica*, 7(4): 283-313, http://www.springer.com/geography/gis+cartography/journal/10707.

Beven, K. J. and Moore, I.D., ed. (1992), *Terrain Analysis and Distributed Modeling in Hydrology*, Wiley, 249 p.

Chas Wallis, Watson, D., Tarboton, D. and Wallace, R. (2009) Parallel Flow-Direction and Contributing Area Calculation for Hydrology Analysis in Digital Elevation Models. Paper presented at the 2009 International Conference on Parallel and Distributed Processing Techniques and Application, Las Vegas, Nevada, USA. July 13th – 16th 2009.

Chow V. T (1959), *Open-Channel Hydraulics*, McGraw-Hill Book Company Inc, New York, International Student Edition.

David R. Maidment (1996), GIS and Hydrologic Modelling – An Assessment of Progress. Paper presented at the Third International Conference on GIS and Environmental Modelling, Santa Fe, New Mexico. January 22 – 26, 1996.

Garbrecht, J. and Martz, L. W, (1997), "The Assignment of Drainage Direction Over Flat Surfaces in Raster Digital Elevation Models," *Journal of Hydrology*, 193: 204-213.

Hellweger, F., (1997), *Agree-DEM surface reconditioning system*.

M. Borga, Fontana, G. D, and Cazorzi, F. (2002). Analysis of topographic control on shallow landsliding using a quasi-dynamic wetness index. Journal of Hydrology, 268(1-4):56–71.

Maidment, D. R., ed. (2002), *Arc Hydro GIS for Water Resources*, ESRI Press, Redlands, CA, 203 p.

Mark, D. M., (1988), "Network models in geomorphology," in *Modelling in Geomorphological Systems*, Edited by M. G. Anderson, John Wiley., p.73-97.

O'Callaghan, J. F. and Mark, D. M (1984), "The Extraction of Drainage Networks from Digital Elevation Data," Computer Vision, Graphics and Image Processing , 28: 328-344p.

Planchon, O. and Darboux, F. (2001), "A fast, simple and versatile algorithm to fill the depressions of digital elevation models," *Catena*, 46: 159-176p.

Ratika. P. et al (2010), " Estimation of Rainfall Runoff using Remote Sensing and GIS in and around Singtam, EastSikkim" International Journal of Geomatics and Geosciences, Vol. 1, Issue 3, 466-476p

Soille, P., Vogt, J and Colombo, R. (2003), "Carving and adaptive drainage enforcement of grid digital elevation models," *Water Resources Research*, 39(12): 1366, doi:10.1029/2002WR001879.

Soojeong Myeong and Hyun Jung Hong (2009). Developing Flood Vulnerability Map for North Korea. A paper presented at SPRS 2009 Annual Conference, Baltimore, Maryland. March 9 – 13, 2009.

Tarboton, D. G and Ames, D. P, (2001) Advances in the mapping of flow networks from digital elevation data. In World Water and Environmental Resources Congress , Orlando, Florida, May 20-24, ASCE, http://www.engineering.usu.edu/cee/faculty/dtarb/asce2001.pdf.

Tarboton, D. G, (1997) A new method for the determination of flow directions and contributing areas in grid digital elevation models. Water Resources Research, 33(2):309–319p.

Wilson, J. P. and Gallant, J. C. (2000), Terrain Analysis: Principles and Applications, John Wiley and Sons, New York, 479 p.

BIOGRAPHICAL NOTES:

Mr Odumosu, Joseph Olayemi is a first Class Graduate of the Department of Surveying and Geoinformatics, Federal University of Technology, Minna (2010). With several field experiences in Engineering Surveying and Country mapping, he is presently a Postgraduate Research Student of the Department of Surveying and Geoinformatics, University of Lagos, Nigeria. His research interest is in Geodesy, Spatial Analysis and Simulation of Earth Geodynamics.

Mr. Oluibukun Gbenga AJAYI is a First Class Graduate of The Department of Surveying and Geoinformatics, Federal University of Technology, Minna in 2010. He currently works as a Graduate Assistant with Surveying and Geoinformatics Department, Federal University of Technology, Minna and also a Postgraduate Research Student of the Surveying and Geoinformatics Department, University of Lagos. He majors in GIS, Remote Sensing and Photogrammetry.

Mr. Ekundayo Adesina is an academic Staff of the Federal University of Technology, Minna. He majors in Geographic Information Sciences.

CONTACTS

Name: Olayemi Joseph, ODUMOSU
Institution: Federal University of Technology, Minna
Address: Surveying and Geoinformatics Department, Federal University of Technology, Minna.
City: Minna, Niger-State
Country: Nigeria
Tel. +2348065916462
Fax: Nil
Email: odumossu4life@yahoo.com
Website: Nil

Name: Oluibukun 'Gbenga, AJAYI
Institution: Federal University of Technology, Minna
Address: Surveying and Geoinformatics Department, Federal University of Technology, Minna.
City: Minna, Niger-State

Country: Nigeria
Tel. +2348036832797
Fax: Nil
Email: ogbajayi@gmail.com
Website: Nil

Name: Ekundayo, ADESINA
Institution: Federal University of Technology, Minna
Address: Surveying and Geoinformatics Department, Federal University of Technology, Minna.
City: Minna, Niger-State
Country: Nigeria
Tel. +2348038095866
Fax: Nil
Email:
Website: Nil