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From Spot Heights to Cell Heights: the Data Structure and the Dynamics of the Digital Elevation Model

BY

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1.0 INTRODUCTION

- The central place of topography in all aspects of environmental evolution and phenomena has been noted.
  - Topography is a critical factor in soil-forming processes because it influences a number of factors including hydrological and thermal regimes of soils through climatic and meteorological characteristics.
  - Topography is also at the base of gravity-driven lateral transportation of water and other substances both at the surface and subsurface levels.
  - Spatial distribution of vegetation cover is influenced by topography due to the interaction of scaled endogenous and exogenous processes.

INTRODUCTION contd.

  - Equally, topography of an area can be a pointer to the geological structure of the terrain. (Florinsky, 2012).
- All these show the centrality of the topographic information as is increasingly being employed in qualitative and quantitative analyses in the geosciences.
- The need to improve the knowledge of how terrain features such as topography, soil type and vegetation, interact with atmospheric events to create environmental phenomena including flooding and erosion are at the foundations of the growing drive to account for the contribution of each piece of land in its own form.

INTRODUCTION contd.

- What has become of keener interest is not as much of digitalization of topographic data as it is the piecewise quantitative topographic characterization of every bit of landscape in the area of interest.
- The very dynamic DEM structure calls the surveyors to move the structuring of topographical information from spot heights structure to cell heights structure data formats that may directly be used in various types of analyses of the terrain topography
- This paper while presenting the trends of research in continuous topographical surface representations is also a call for the review of the curricula of topographical surveying, digital cartography, and GIS for surveyors to include the basic training needed for expressing topographical information in Digital Elevation Model (DEM) structures and of using the DEM in environmental analyses.

Commonly Associated Terms

The term DEM, is increasingly being associated with grid cell representation of the bare earth terrain surface that are populated with elevation values of the ground they represent.

A Digital Terrain Model (DTM) is an elevation model of the bare earth terrain surface, based on Triangulated Irregular Network (TIN) including breaklines and linework to help define edges of TIN triangles, or to enforce the downward flow of water in the drainage feature.

The DEM or DTM may be employed with other measurable environmental phenomena in Digital Terrain Analyses (DTA) that leads to modelling land based phenomena. For instance the DEM or the DTM may be employed in runoff flow Digital Terrain Analysis, based on rain storm event leading to runoff flow modelling needed for delineation of drainage routes, erosion modelling, and flooding vulnerability studies, etc.

Some DEM based Terrain Phenomena Analyses

A number of the evolving terrain phenomena analyses include:

- Delineation of hydrological features such as streams, drainage routes and ridges,
- Sediment transportation analyses
- Demarcation and characterization of sub-catchments of watersheds,
- Erosion potential modelling,
- Flood potential modelling and their derivatives such as flood cost analyses.

Some DEM based Terrain Phenomena Analyses Contd.

- morphological analysis of landforms, site and route selection analyses in civil engineering.
- inter-visibility analyses
- Terrain analyses in soil and geological sciences
- Analyses for delineation of physiographic units and so on.

2.0 TRENDS IN DIGITAL ELEVATION MODELLING

- Since adapting electronics in surveying, topographic data has been stored electronically as digital data in discrete x, y, z form especially as spot heights
- Contour lines are stored in digital forms with the identity of their elevation values and populated by sequential points of x, y coordinates and generated in computer graphics with spline (smoothening polynomial) functions.
- The digital contour and spot height are deficient for quantitative environmental analyses because the elevation so defined do not characterize defined land units.
- Two types of Digital Elevation Models are becoming established as normative. The grid Digital Elevation Model (DEM) and the Triangulated Irregular Network (TIN) are proving very useful forms of the Digital Elevation Model.

2.1 The Triangulated Irregular Network (TIN)

- The Triangulated Irregular Network (TIN) is an irregular assemblage of planar triangles which vertexes (nodes) are formed at points known in 3–D (x, y, z). These vertexes are carefully chosen to meet triangulation and the Delaunay conditions.
- i) The basic figure so formed are only triangles.
- ii) The entire land space is completely divided into triangles
- iii) No edges of triangles should intersect at a point that is not a vertex.
- iv) No vertex of the triangles is inside the circum-circle of any of the triangles - the Delaunay condition.

2.1.1 Conditions for Triangular Irregulated Networks (TIN)

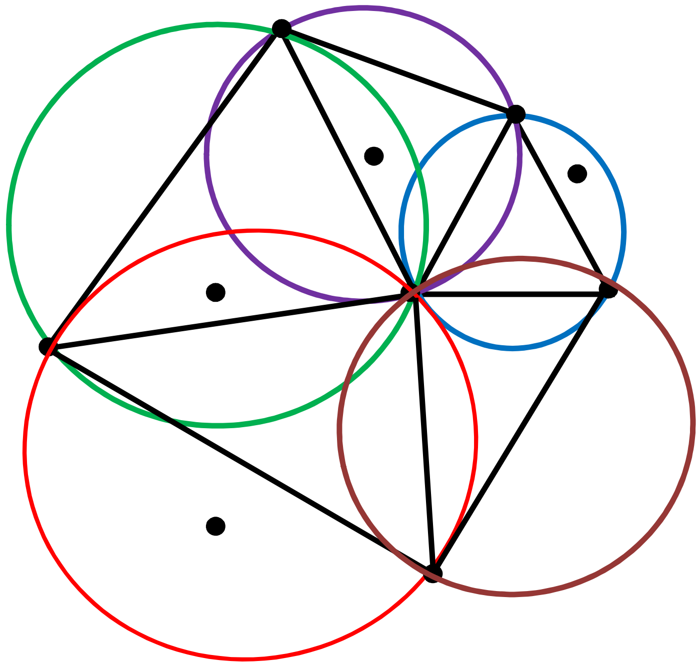

Fig 1: The TIN Triangulation and Delaunay Conditions.

2.2 The Grid Digital Elevation Model

- In a grid Digital Elevation Model, the land space is divided into a grid of rectangular cells, where each cell value represents the elevation of the land surface.
- The DEM internal data structure may be a constant elevation or an averaging function at the center point inside the square (Kreveld, 1996).
- Due to the efficiency of the grid DEM, the term Digital Elevation Model is increasingly being associated with the grid form only (Maidment, 2002).

2.2.1 LAYOUT OF THE GRID DIGITAL ELEVATION MODEL

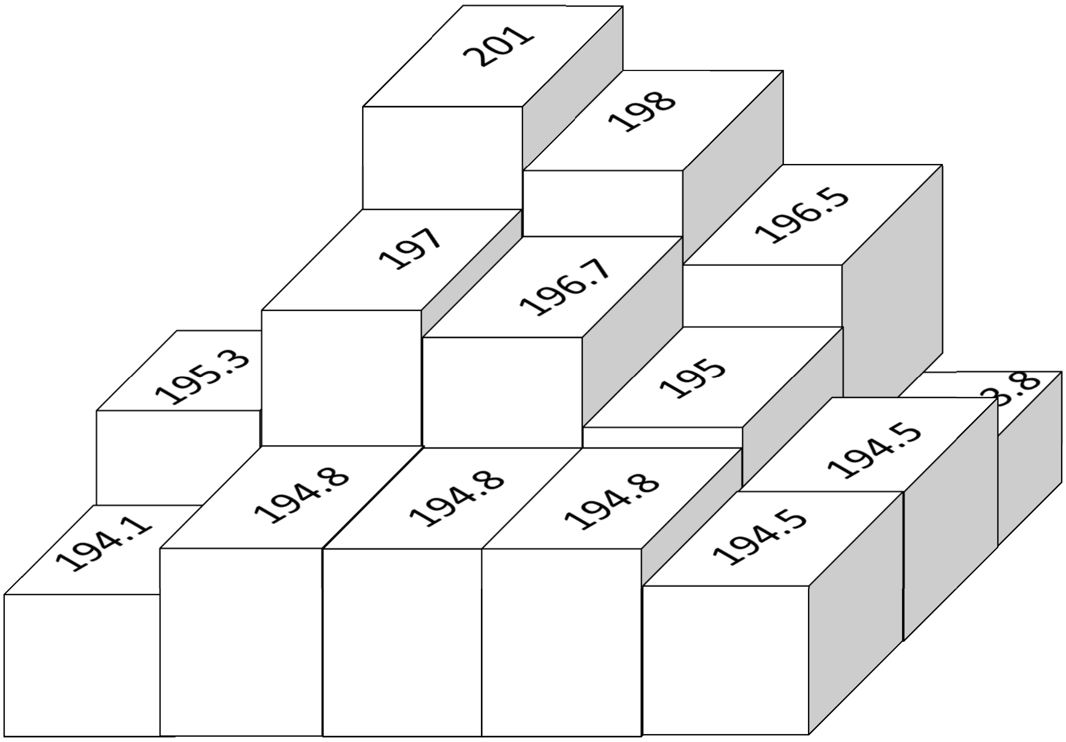

Fig 2: The grid Digital Elevation Model scheme.

2.2.2 MATHEMATICS OF REPRESENTING THE TOPOGRAPHIC SURFACE WITH DEM

- The mathematics of the representation of the topographic surface with a DEM could address relatively small areas so that the assumption of plane holds.
- Two-dimensional (piecewise) continuous functions may be used to define relatively small portions of the topographic surface (Jancaitis, 1978; Strakhov, 2007; Florinsky, 2012).
- For large areas, the fact of a curvilinear surface would imply that spherical functions be used to define the topography of such areas Schroder and Sweldens (2000); Wieczorek, (2007); Florinsky (2012)

2.2.3 DIGITAL ELEVATION MODEL SIZES

- The grid Digital Elevation Model divides the entire landscape under question into regularly sized rectangular elevation cells using grids.
- If the DEM cell represents a very large area in non-flat areas, the credibility of the DEM will be in question and the result of the mathematics will not match natural occurrences in the field.
- The choice of the size of cells should be masterfully carried out as a linearization of topographical polynomials of the morphology of land space, so that when integrated, the result of the linearization will match the result of executing the polynomial directly to a very reasonable extent.
- Smaller cell sizes where possible will be advised. This however places a challenge on the computer memory, and is only necessary if there is enough data to populate each cell uniquely.

2.2.4 ADVANTAGES OF GRID DEM

- The use of contour lines and triangulated irregular networks for delineating catchment boundaries and flow paths may provide reliable results, however, they require extensive data storage and computation time.
- The computational efficiency and the availability of topographic databases are making the grid cell elevation model gain widespread application for analyzing hydrological problems (Bertolo, 2000).
- The simplicity of the grid DEM and its adaptability makes it the most popular one considering that it has been repeatedly argued that DEMs should be generated considering critical elements of the topographic surface. Florinsky, (2012); Mark, (1979).
- Furthermore, gridded DEMs have been shown to produce higher accuracy than TIN-based DEMs Kumler, (1994).
- Since morphometric variables are usually derived from gridded DEMs, the use of plane grids is reasonable. To convert irregular grids to regular ones will require further interpolation (Florinsky, 2012).

3.0 APPLICATION ISSUES OF THE DEM

- The method of Digital Elevation Model assigns elevation value to each unit of horizontal area.
- Unlike the traditional forms of topographic representation, such as the spot height and the contour, every point in the DEM has an elevation value.
- These DEM cells can be attributed further with other terrain characteristics such as vegetation, soil type, erosivity, etc. These attributes may be done either as single cells or in clusters representing some geographical zones of uniform characteristics in different terrain models.
- Some major weaknesses of the DEM include that it generalizes the elevation of each cell and makes the terrain appear to be a system of steps. However the cell size of the DEM can be made extremely small that for all practical purposes the cell size will represent a spot relative to the size of the landscape. This will only challenge the memory space and processing speed of the computer as the number of cells increases.

3.0 contd. APPLICATION ISSUES OF THE DEM

- DEM data have become an integral part of geographic information systems (GIS).
- Areas of terrain analyses where DEM are already being employed include:
  - Hydrological modelling for flood simulation.
  - Delineation and analyses of watersheds and drainage networks.
  - Soil erosion and sediment transport modelling.
  - Landslide hazard assessment plus delineation and study of physiographic units.

3.0 contd. **APPLICATION ISSUES OF THE DEM**

– Geomorphological evaluation of landforms plus soil and ecological studies.

– The DEM is also being employed in civil engineering and military applications including site and route analyses, and inter-visibility analyses.

– The DEM is equally being used for 3D analysis for enhancement of remotely sensed image.

– Digital topographic data are essential components of groundwater and climatic models.

– DEM has the advantage of not being blurred by land cover features which is often the case when stereo-aerial photograph interpretation and remotely sensed image analysis are used in creating DTMs (Jordan, 2007).

3.1 Sources and Accuracies of DEM

- GROUND SURVEYS
  - Ground survey methods produce only heights of spots to mm accuracies which may then be interpolated to get the DEM.
  - It is limited in the area it can cover. Global Navigational Satellite Systems (GNSS) and photogrammetric surveys are useful in this regard as the GNSS provide for faster production of highly accurate ground controls while the photogrammetric methods using the established ground controls provide for a far wider coverage of the land space with elevation accuracies comparable to purely ground survey methods.
- REMOTELY SENSED DATA
  - The Remote sensing data sources make it possible to determine heights of each cell of the DEM directly.
  - In this case then the elevation of each cell is determined theoretically by aggregating all the heights possible in each cell.
  - However the remotely sensed data sources have their own accuracy issues and will definitely affect the accuracy of the DEM derivative.

3.1 contd. Sources and Accuracies of DEM

- ACCURACIES
  - Ground Survey methods have achieved DEM of 0.60m over a very wide area (author's lab result).
  - For heights from SPOT images standard deviations of 2.97m for flat and open terrain and 3.66m for forest areas have been achieved.
  - For heights from SRTM X-band 3.97m for open and 4.49m for forest areas have been achieved.
  - While for SRTM C-band, 4.25m for open and 6.14m for forest areas have been achieved and for ASTER 7.29m for open and 8.08m for forest areas have been achieved (Sefercik et al, 2007).

3.2 A Sample Application of Digital Elevation Model in Delineating Drainage Routes

- A sample use of the DEM in environmental phenomenon analyses was carried out in Owerri South East Nigeria to determine the storm water runoff natural flow routes using a DEM of the project area.

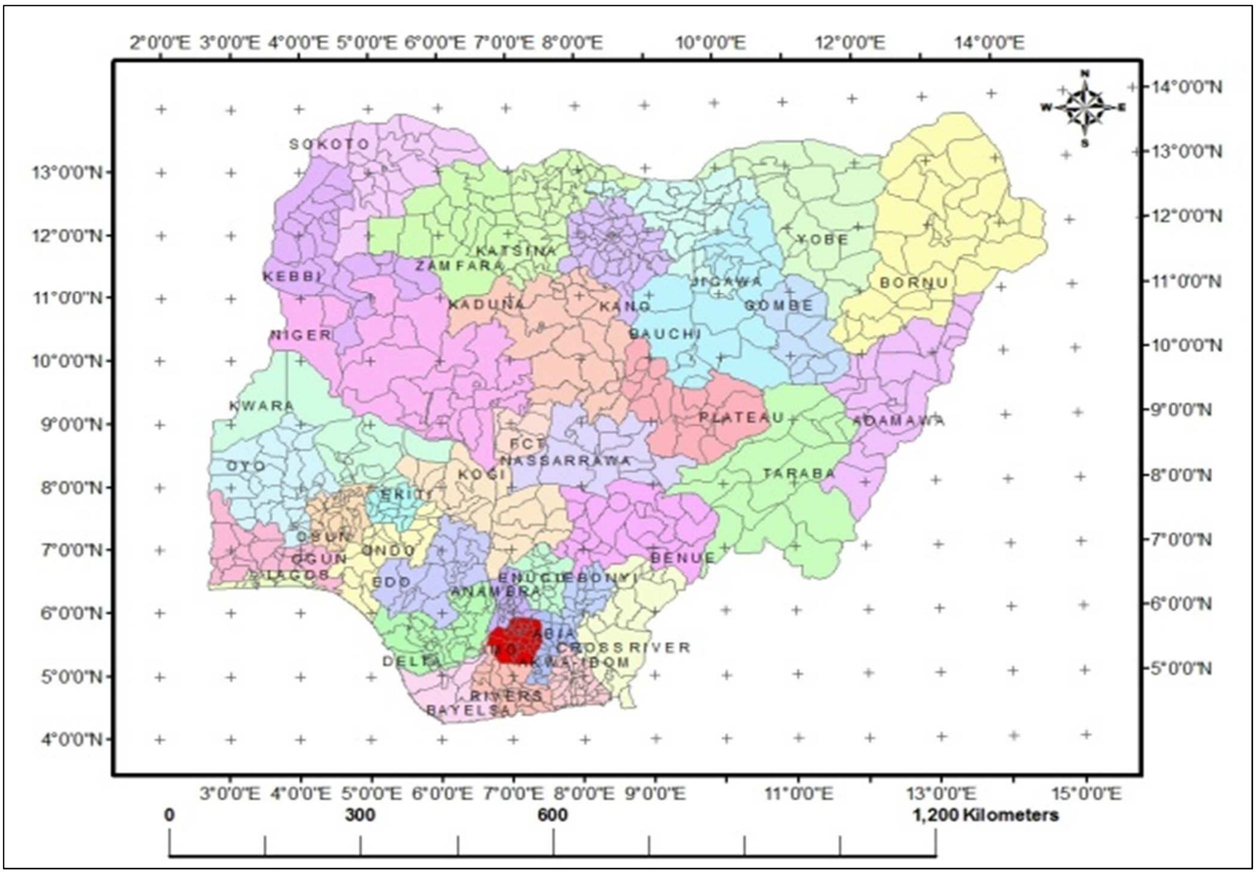

Fig. 3.1a Map of Nigeria with LGAs, showing Imo State South East Nigeria in deep red colour

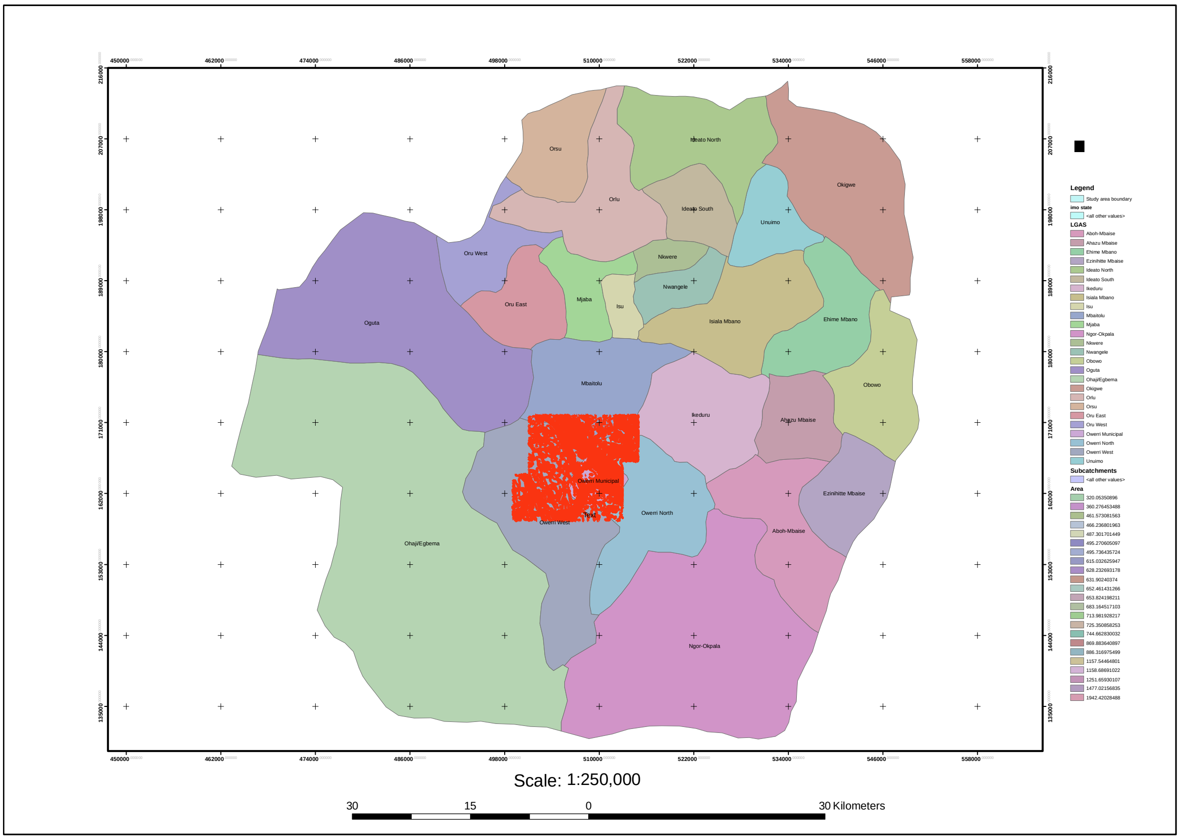

Fig. 3.1b Map of Imo State with LGAs, showing the project area in red

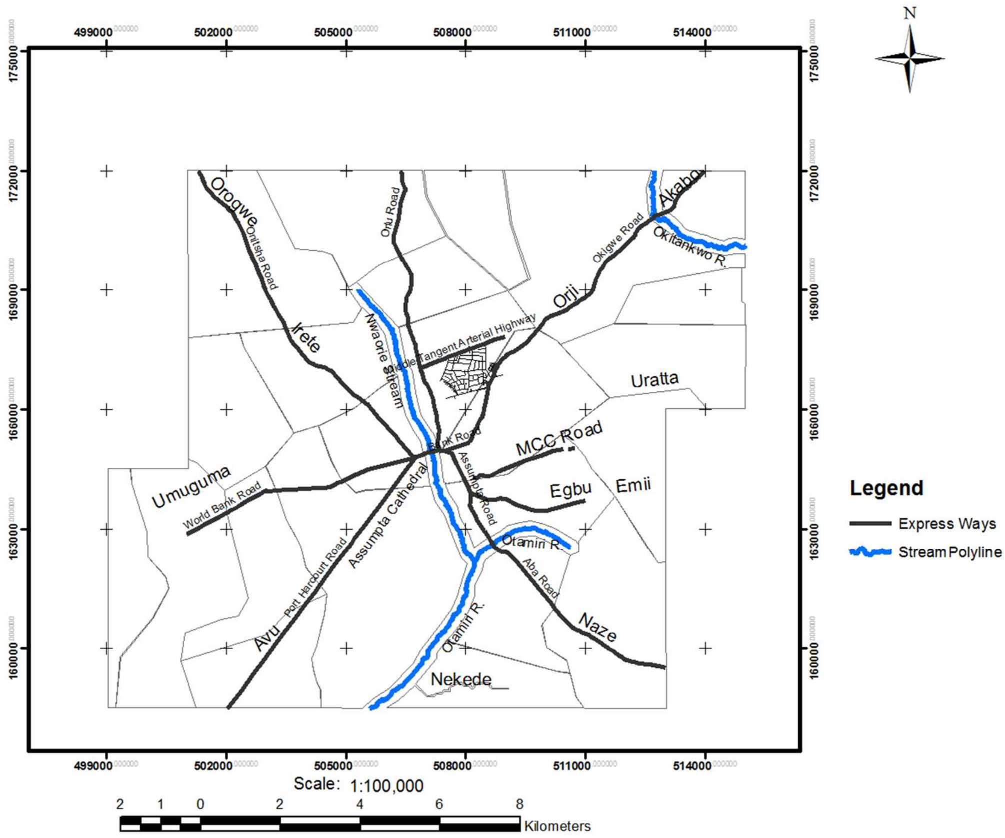

Fig 3c: Map of the Project Area

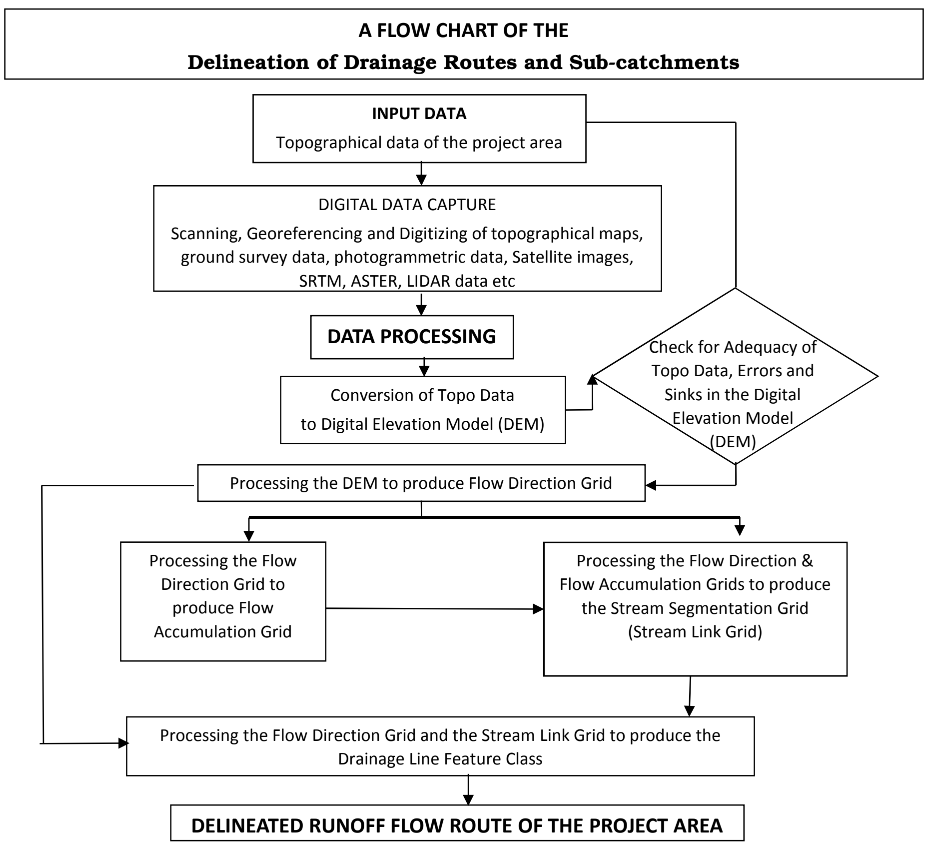

Fig. 4 Flow Chart of the DEM based delineation of drainage routes and sub-catchments

3.2.1 DATA ACQUISITION

- The research essentially involved the analysis of topographic data of the about ***186.024 Sq. Km, (18,602.3857308 Ha***) project area.
- Thankfully ***topographic maps*** of the wide area of coverage of Owerri Nucleus area were made available by the Imo State Surveyor General and the Head of the Survey Department, Owerri Capital Development Authority.

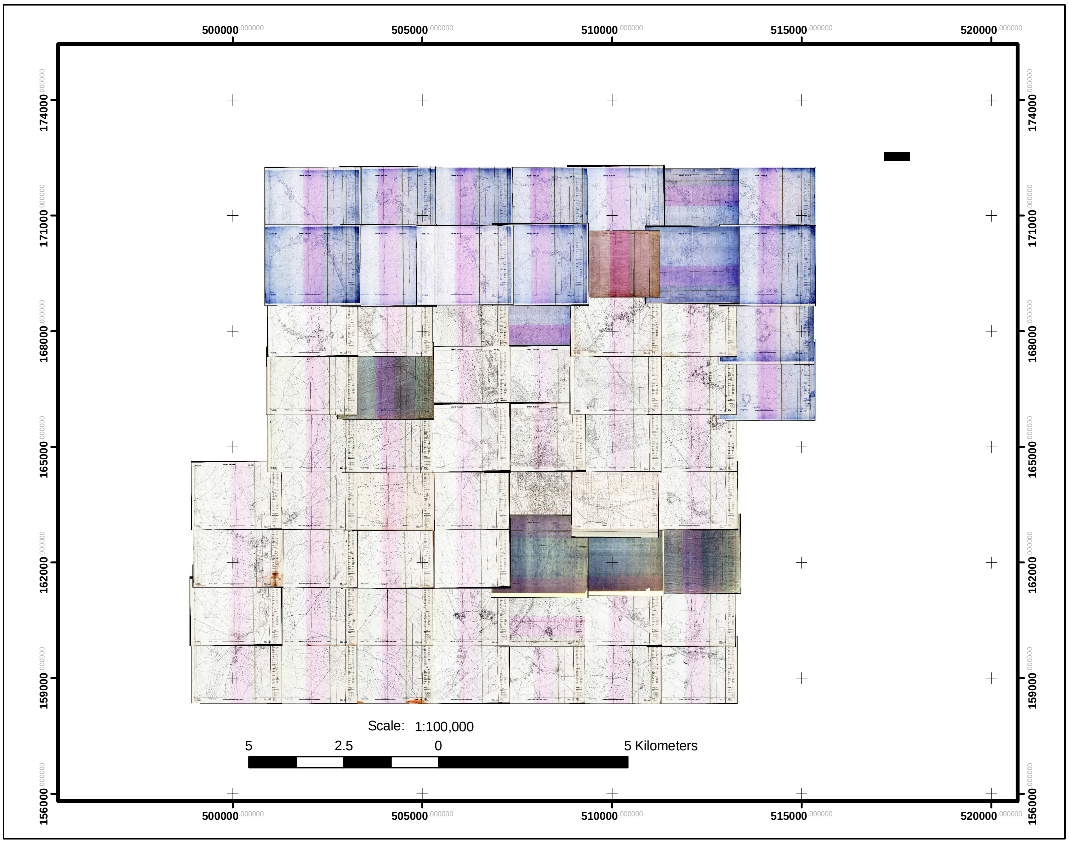

Fig. 5 Georeferenced Topo Maps of the Project Area in mosaic

THE RESULTING DIGITAL CONTOUR OF THE PROJECT AREA

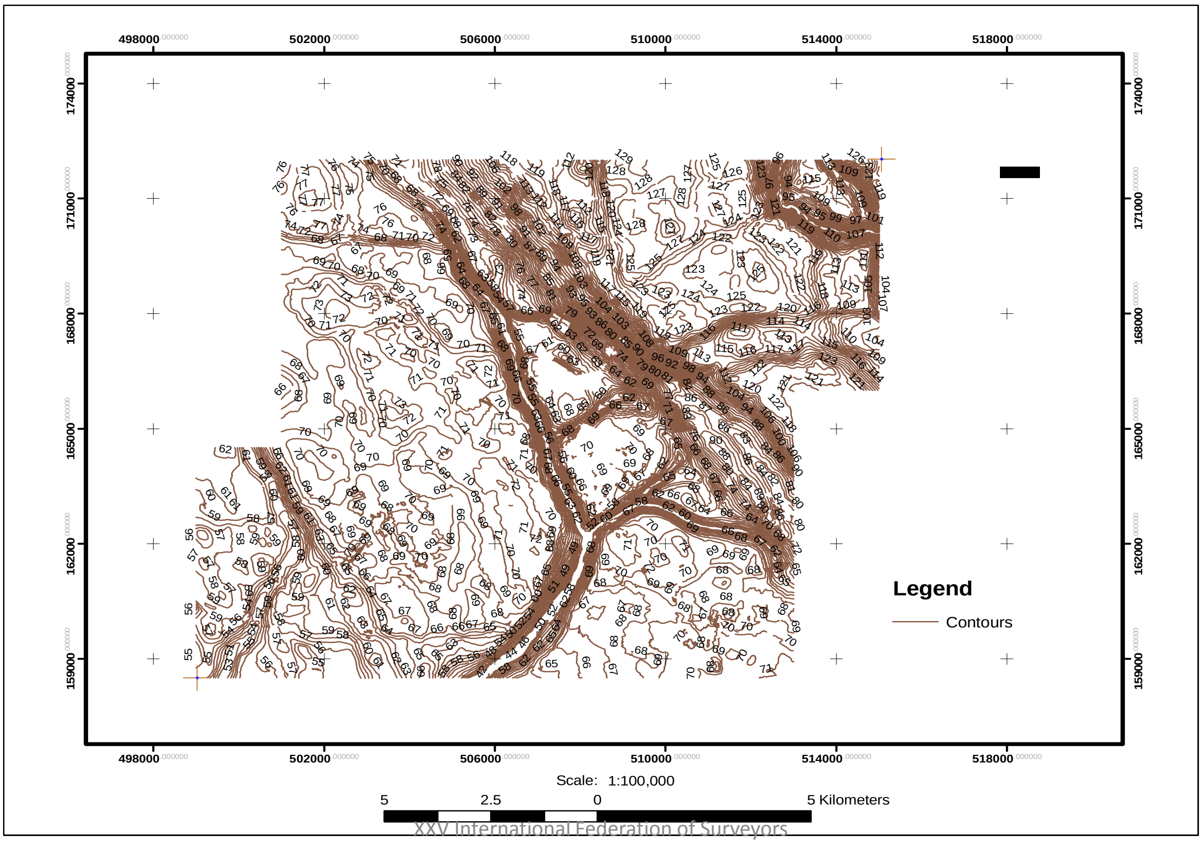

Fig. 6 Resulting Contour of the Project Area

THE RESULTING DIGITAL SPOT HEIGHT OF THE PROJECT AREA

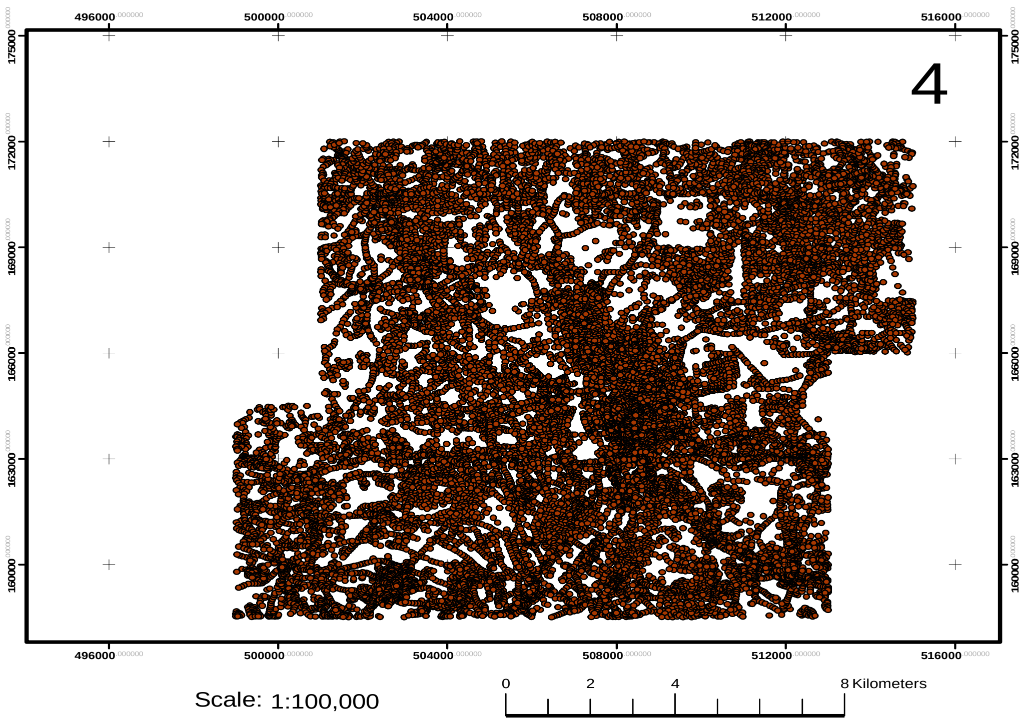

Fig. 7 Resulting Spot Height of the Project Area

3.2.2 DATA PROCESSING AND ANALYSIS

DEM The Digital Elevation Model (DEM) created in ArcGIS using the contour features. The DEM is a digital grid in which each cell holds the elevation value of the land space the cell represents.

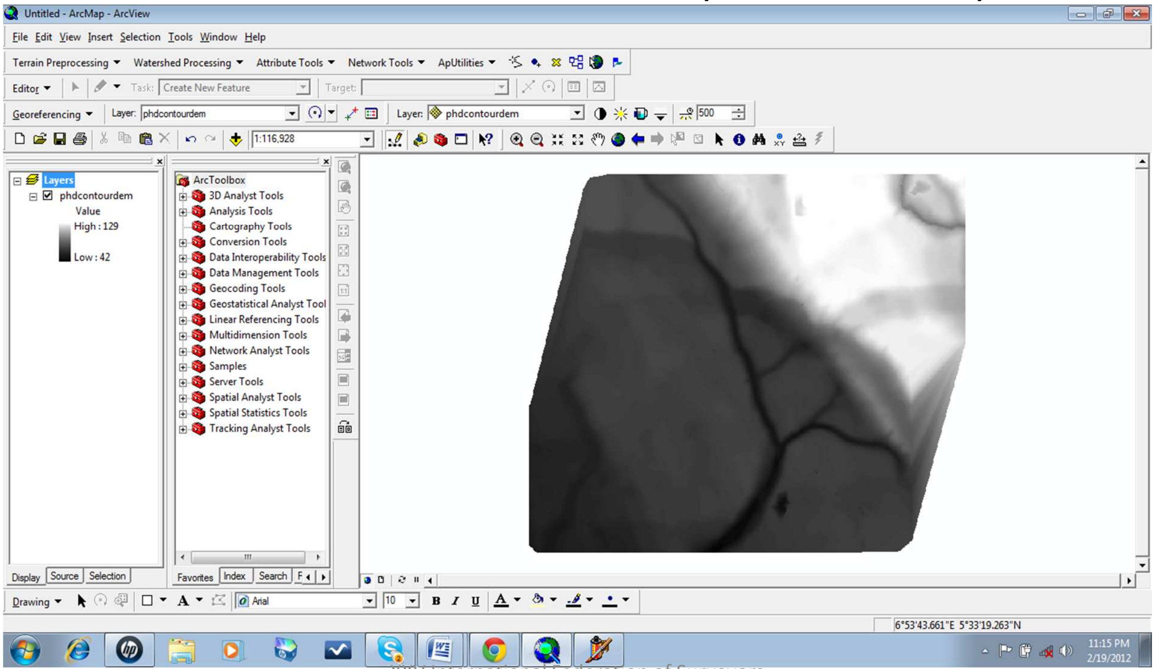

Fig. 8 Screen Print of DEM of the Project Area

3.2.3 DEM VALIDATION

The DEM was validated using orthometric heights derived from GPS surveys of random points across the project area. The full details are in the paper proper. But Table 1 shows the statistics

Table 1: Statistics of the Validation: GPS orthometric height value minus DEM value

	All Points 1 - 57	Only Points 5 - 57
Range	9.374	3.934
Average	-0.509	0.173
RMSE	1.947	0.598

COMPARING WITH OTHER POSSIBLE

SOURCES OF DEM	RMSE – Open Areas	RMSE – Forest Areas
SPOT - flat terrain	2.97m	3.66m
SRTM X-band	3.97m	4.49m
SRTM C-band	4.25m	6.14m
ASTER	7.29m	8.08m
Validated Topo Map	Without and outlier distorted site 0.598m	With 2% outlier of badly distorted site 1.947m

3.2.4. PROCESSING DEM TO DELINEATE RUNOFF NATURAL FLOW ROUTES

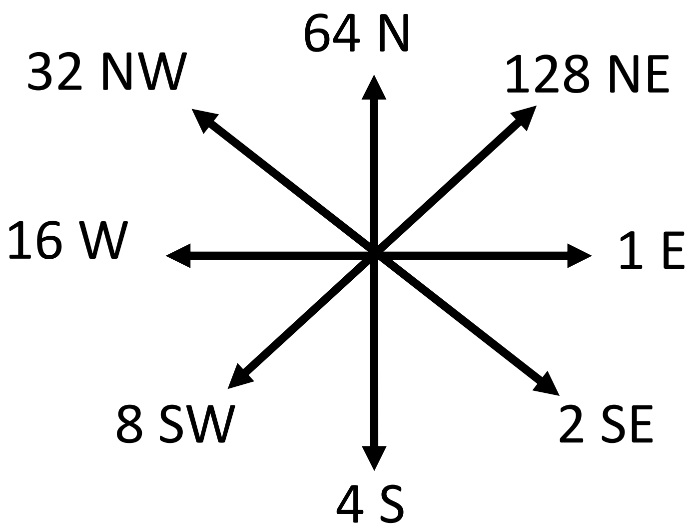

Fig. 9 Flow Direction Scheme

141	140	140	141	142	142	141	142
139	138	137	139	139	139	139	140
138	135	135	136	137	136	137	139
134	134	132	134	135	134	136	138
131	131	129	133	133	132	134	137
128	127	126	132	131	130	132	133
126	123	124	126	128	129	131	133
124	120	125	127	129	129	130	132

DIGITAL ELEVATION MODEL

2	2	4	8	4	4	4	8
2	4	4	8	2	4	8	8
4	2	4	8	2	4	8	2
4	2	4	8	2	4	8	8
2	2	4	8	2	4	8	4
2	4	4	8	8	8	16	16
2	4	16	16	16	16	16	16
1	0	16	32	32	32	16	16

FLOW DIRECTION SCHEME

Fig. 10 Digital Flow Direction Scheme

1	1	1	1	1	1	1	1
1	2	4	1	2	2	3	1
1	3	5	1	1	8	2	1
2	1	10	1	1	12	1	1
3	3	12	1	1	12	2	1
1	4	17	1	1	17	2	1
1	53	47	27	24	3	2	1
1	57	1	1	1	3	2	1

Figure 11 Flow Accumulation Grid

		1					
		1			1		
		1			1		
		1			1		
		1			1		
	1	1	1	1			
	1						

Figure 12 Drainage Route Cells

Runoff Flow Routes

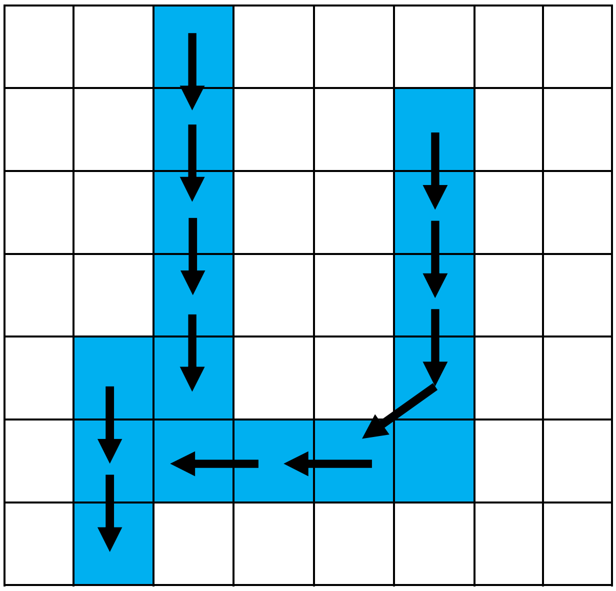

Figure 13 Drainage Route

20-cell Stream Definition Grid Scheme

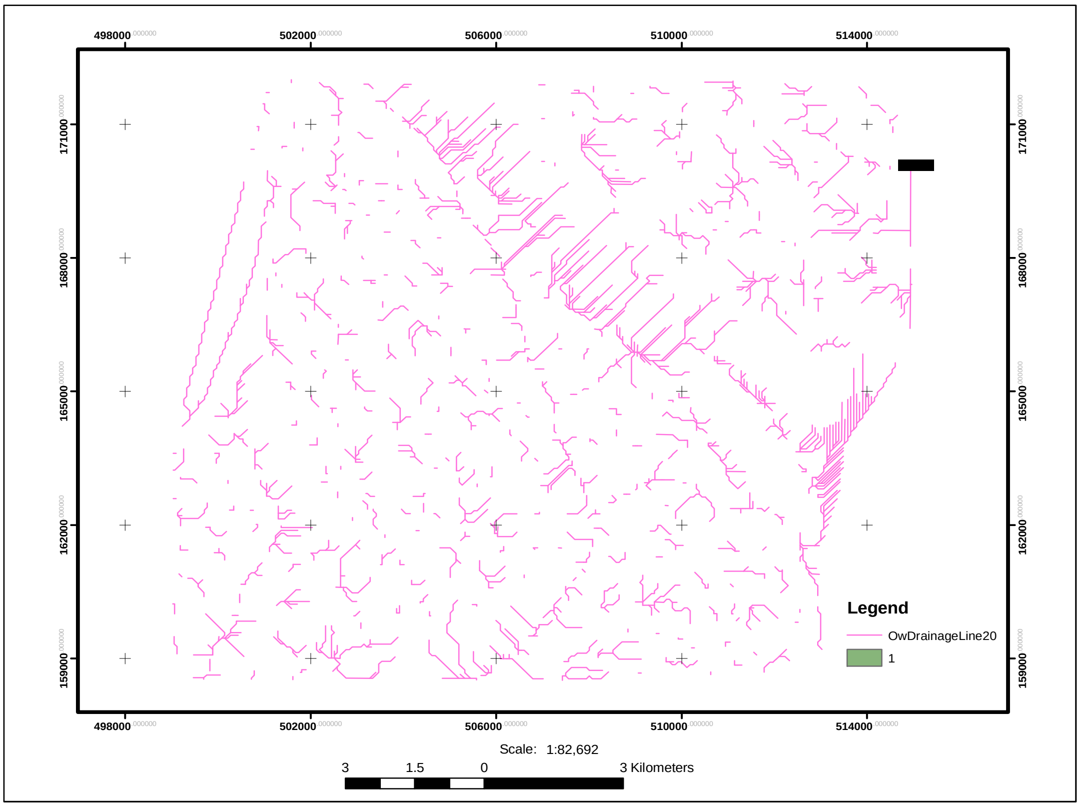

Fig. 14 Stream Definition Grid of the project area using 20 cell accumulation threshold

140-cell Stream Definition Grid Contd.

- The resulting Stream Definition Grid is shown hereunder

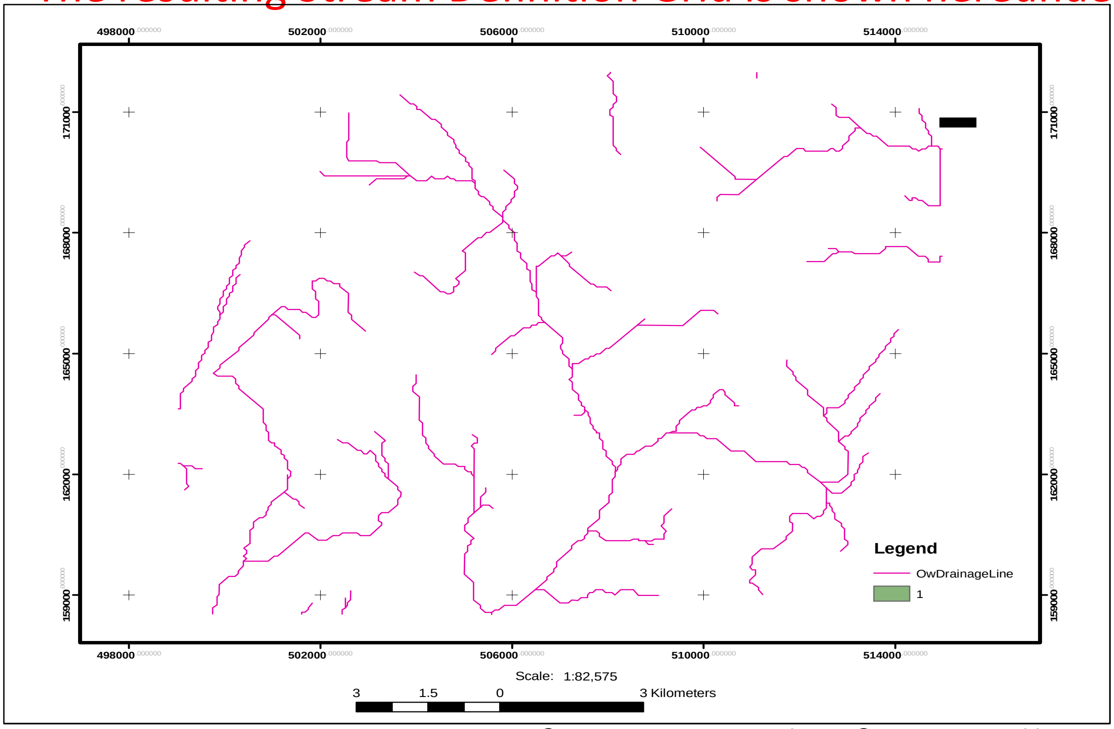

Fig. 15 Stream Definition Grid of 140 cell accumulation threshold

Drainage Line Processing

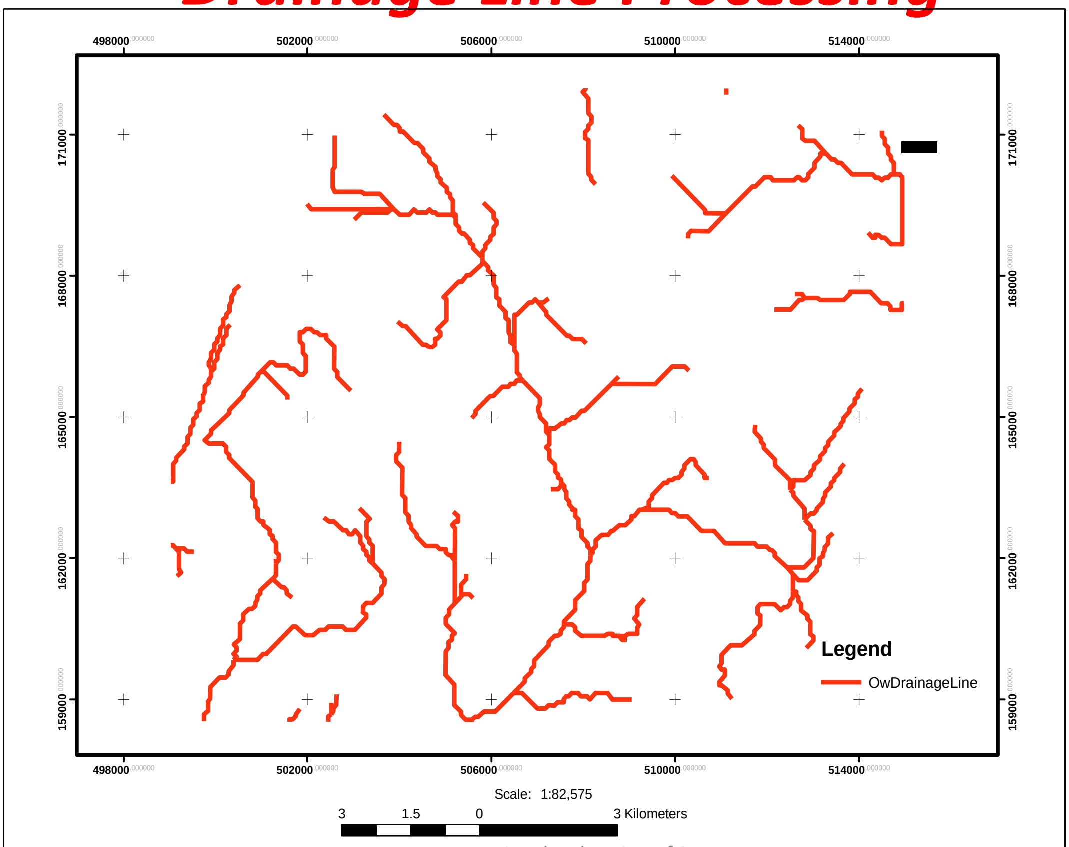

Fig. 16 Owerri Drainage Network.

Manually generated drainage area polygons with the drainage lines creates the drainage map

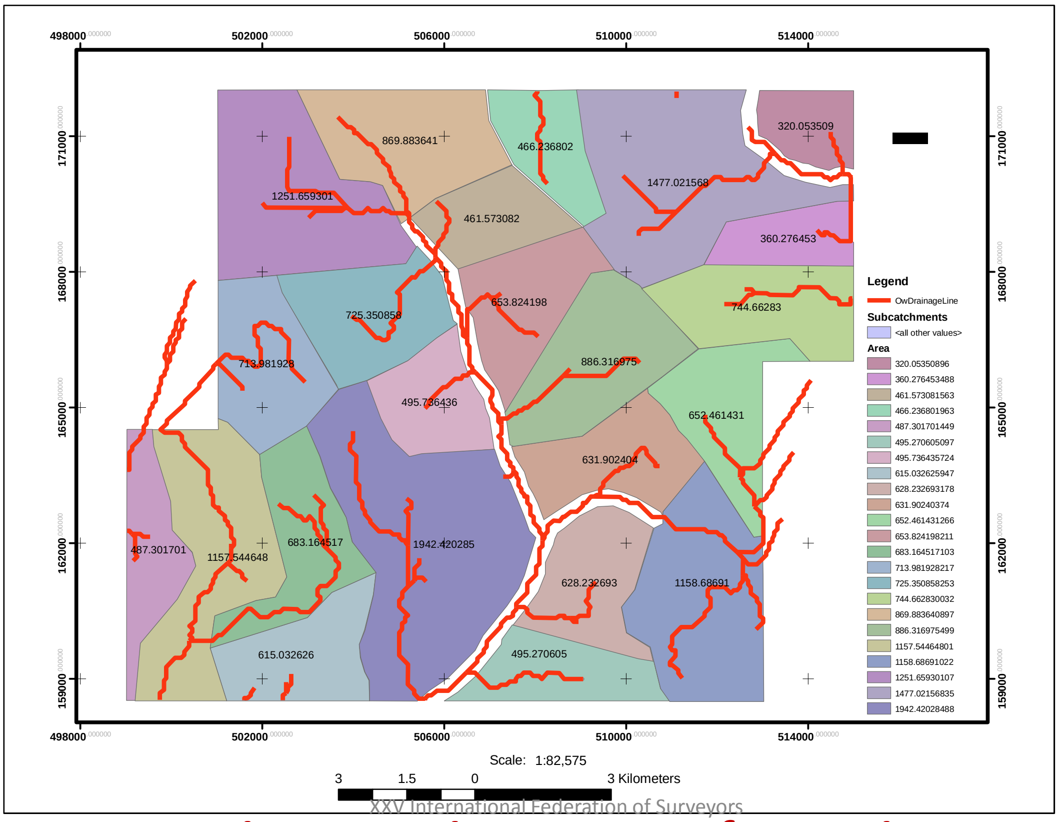

Fig. 17 Drainage Map of Owerri

3.2.5 SITE VALIDATION OF DRAINAGE AREAS

On 6th October 2011 and 20th July 2012 visits were taken to 3 of the sites delineated in the analyses to be drainage lines to check their state of flooding or otherwise after the rains. It was discovered that they were heavily flooded. The photographs presented hereunder are those of the visited sites.

- .

Works Layout Area 6th October 2011 : Conduit C11 series. Fully developed pond now due to high runoff coefficient of a developed urban area.

Plate 1

Works Layout Area 6th October 2011 : Conduit C11 series.

Plate 2

Works Layout Area, 6th October 2011: Conduit C11 series.

Plate 3

Federal Housing Estate 20th July 2012: C14 series

Plate 4

Federal Housing Estate: 20th July 2012 C14 series

Plate 5

Federal Housing Estate: 20th July 2012 C14 series

Plate 6

Federal Housing Estate: 20th July 2012 C14 series

Plate 7

Chukwuma Nwoha Road Area 20 July, 2012: C14 series

Plate 8

3.2.6 Results and Discussion

- The demarcation of the natural flow routes holds an advantage in selecting best drainage routes for the drainage network design of the city.
- This is very useful both in designing the main network of a virgin area for future development, or when responding to drainage needs of an already existing urban area.
- The demarcated flow routes are of high advantage in drainage design since the slope of the routes, their lengths and their end coordinates are extracted as results of the research on a GIS platform.
- The results of the research also include the delineation and characterization of the straight units of the flow routes and the determined 23 sub-catchments of the project area of Owerri.

3.2.6 Results and Discussion Contd.

- These are very important tools in flood mitigation, erosion control, urban area planning, urban development monitoring and management, engineering design of drainage facilities, the studies of distribution of water borne diseases, sediment transportation and agriculture.
- The results of the research demonstrate the importance of the DEM in the analyses of flow environmental phenomena such as erosion, sediment transportation and flooding analyses and modelling and so on.

4.0 SURVEYOR - EDUCATION ISSUES FOR DEM DEVELOPMENT

- Training curricula of Colleges and Universities in the developing world are reviewed relatively slowly. The need to develop curricula that equip students of Surveying and Geoinformatics in Nigeria and possibly other parts with the necessary skills required for the processing and application of the highly dynamic topographical data structures of the Digital Elevation Models is obvious.
- It has been suggested elsewhere that the need to continually developing and improving efficient algorithms on terrains is an interesting area of research. It notes that the GIS developers, GIS researchers, and computational geometers can work together to develop a number of elegant and efficient solutions to practical problems on terrains. The analysis of efficiency of these solutions should be based on realistic assumptions on terrains Kreveld (1996).

4.0 CONCLUSION AND RECOMMENDATION

4.1 CONCLUSION

- It is obvious that the Digital Elevation Model (DEM) is the way forward for quantitative and qualitative oriented topographical and environmental analyses.
- In the entire field of the geosciences the use of the DEM for terrain phenomenon characterizing and modelling and Digital Terrain Analysis (DTA) is obviously unlimited.
- The DEM has been shown to be the most important factor in the Digital Terrain Model and this is an indicator of the central position of properly skilled surveyors across the field of the geosciences.

4.2 RECOMMENDATIONS

- DEM development as a computational science is being driven by computational geometry. The need however remains for the role of the surveyors given the complex issues of datum transformations, geoidal models, accurate geospatial measurements and georeferencing or geolocation for all geospatial analyses.
- The call for the development of curricula of the institutions that train surveyors to include training for skills needed for expressing topographic data in the Digital Elevation Data Structure and for effective application of the DEM is inevitable.

THANK YOU

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