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

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SUMMARY

This paper notes the increasing growth of the use of the Digital Elevation Model (DEM) in Digital Terrain Analysis (DTA) and terrain characterizing and phenomenon modelling. It explores ongoing researches in the data structures and applications of the Digital Elevation Model. The different data structures of the Triangulated Irregular Network (TIN) and the grid Digital Elevation Model are presented. Sources of DEM data and their possible sources of errors and their accuracies are discussed.

One notable area where the DEM has been very successful in Digital Terrain Analysis (DTA) is in the area of delineating drainage routes and marking out sub-catchments. The scheme of this analysis is discussed. Processing the DEM produces the Flow Direction Grid, this is processed to determine the number of cells that their runoff will flow into a given cell, producing the Flow Accumulation Grid, and then the stream link grid is produced.

The paper points out that obviously the topographic content represented by the DEM is the most important factor in the terrain characterization and terrain phenomenon modelling such as stream and drainage route and ridge delineation, erosion modelling, flood risk potential simulation, etc. It is the DEM that is used in various Digital Terrain Analysis (DTA) of all branches of the geosciences. The paper then calls for the training of surveyors with the skills for developing the Digital Elevation Models and to apply the same.

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1. INTRODUCTION

The needs to accurately compute and simulate environmental phenomena are driving the efforts to organize landscape data in structures amenable to quantitative and qualitative analyses. Traditionally the topography of land spaces have been presented on paper maps as spot heights or contour lines. These forms of topographic data structures limit themselves to be used for interpolation, profiling and aspect type analyses because those traditional structures of elevations so expressed are not attributes of any defined units of land space.

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. Equally, topography of an area can be a pointer to the geological structure of the terrain. (Florinsky, 2012). The foregoing points show the centrality of the topographic information as is commonly 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. 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.

A Digital Elevation Model (DEM) is a very dynamic topographic digital data structure. The term 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.

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 data in Digital Elevation Model (DEM) structures and of using the DEM in environmental analyses.

2. EVOLVING TRENDS IN DIGITAL ELEVATION MODELLING

Since the beginning of adapting electronics in surveying topographic data has been stored electronically as digital data in discrete x, y, z form especially as spot heights. Advances in digital cartography have also enhanced the storing of contour lines in digital forms. Each line is stored 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.

Digital contour as a surface model lacks full dynamism since a contour line is usually stored as a sequence of discrete points using their x and y coordinates and assigning an elevation value to all the points that fall along the line linking these points. Contours are therefore amenable to interpolation Kreveld (1996).

Essentially digital contour surface representation data structure is half way into realizing the basic conditions for landscape analyses. The digital contour is deficient on its own because the elevation so defined is not based on any land units. It however provides a population of sample points that is the basis for further processing to Digital Elevation Models, having topographic data structures that are based on defined land units. A basic requirement for Digital Elevation Models is that they must account in a quantitative manner for the elevation of every piece of land. This is the basis for characterizing landscapes in catchments and sub-catchments, in soil types, for erosion potentials, for flooding potentials which may then be employed in efficient analysis of environmental phenomenon.

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. In the grid DEM the landscape is divided by grids into cells. Each cell of the grid DEM has a unique elevation value. In the case of a TIN Digital Elevation Model, the landscape is covered with a network of irregularly shaped and sized triangles. The triangles of the TIN more or less mimic the turn and slope of elevation in the area each triangle covers. There is no unique elevation value for the triangles. However the 3-D coordinates of the 3 corners of each triangle hold the data required and the TIN specifies the functions that compute other required points.

2.1 The Triangulated Irregular Network (TIN)

The Triangulated Irregular Network commonly referred to as TIN is an irregular assemblage of planar triangles which vertexes (nodes) are formed at points of known 3 – dimensional coordinates, x, y, z. These points that form the vertexes are carefully chosen to meet triangulation conditions and then the Delaunay conditions as in Fig. 1.

With a set of known points in the land space of interest, the TIN is formed by constructing a network of appropriate triangles with some of the known points as vertexes. In triangulation the following conditions are carefully met.
i) That the basic figures so formed by triangulation are only triangles.
ii) That the triangulation effort divides the entire land space completely into triangles
iii) No two edges of any of the triangles should intersect at a point that is not a vertex.

Effort is made to use well-formed triangles only. A criterion is set for selecting the points that may be used in the triangulation scheme. No point to be so used is inside the circumcircle of any triangle formed in the scheme. This property is known as the Delaunay condition.

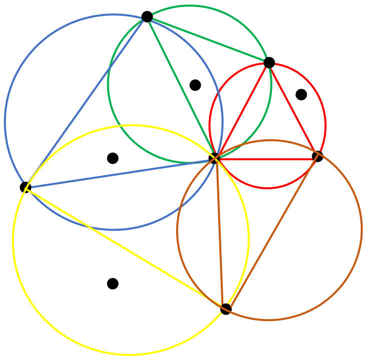

Fig 1: The Delaunay triangulation condition showing some known points not used in the triangulation scheme.

2.2 The Grid Digital Elevation Model

The term Digital Elevation Model (DEM) is increasingly being associated with the grid DEM only. In a 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 (Maidment, 2002). The grid has been interpreted in one of two senses. In the first sense it is in the sense in which its elevation represents the elevation for every point inside the square, implying that the Digital Elevation Model is a non-continuous function. In the second sense, the elevation may be seen to represent only the elevation at the center point of the square, or the average elevation inside the square. When this is the case interpolation method needs to be specified so that the Digital Elevation Model may specify the elevation of all the points represented in the space (Kreveld, 1996).

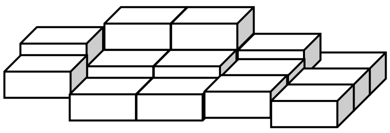

Fig 2: The grid Digital Elevation Model scheme.

The mathematics of the representation of the topographic surface could address relatively small areas so that the assumption of plane may hold, and two-dimensional (piecewise) continuous functions may be used to define relatively small portions of the topographic surface (Jancaitis, 1978; Strakhov, 2007; Florinsky, 2012). In the case of 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).

The grid Digital Elevation Model divides the entire landscape under question into regularly sized rectangular cells using grids. Each cell has a unique elevation value for all the land space in it. 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. This is particularly true for rough terrains. 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.

The advantages of the grid DEM over other types of topographic surface representation are many. 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. Also, 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. APPLICATION ISSUES ON THE DIGITAL ELEVATION MODEL

There are two key advantages in the application of the Digital Elevation Model. The first is that the method assigns a measure of horizontal size to each elevation value. The second is that 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 cells can be attributed further with other terrain characteristics 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.

Already the DEM has been used to accurately determine the surface water flow characteristics of landscapes. Its possibilities are proving increasingly limitless since the DEM provides horizontal and elevation data of every space in the entire landscape, which are useful for mathematical computations. DEM can be used in erosion computations. Given cell data covering the entire area of interest and each cell characterized with soil profile and with accurate knowledge of the rain data of the area, erosion, landslides, flooding, stream flow and more can be calculated. The DEM is also proving very useful in geological studies. More deep seated events such as the movement of plate tectonics can still be understood better by using some DEM at the elevations of the plates, providing the strain and stress factors as they affect each cell and therefore may help in the current interest of earthquake prediction.

Digital Elevation Model data have become an integral part of geographic information systems (GIS) having proved very useful in such terrain analyses as hydrological modelling for flood simulation, delineation and analysis of watersheds and drainage networks. DEMs are employed in soil erosion and sediment transport modelling, landslide hazard assessment plus delineation and study of physiographic units. DEM is also being applied in geomorphological evaluation of landforms plus soil and ecological studies. The Digital Elevation Model 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. Digital terrain models (DTM) seek to characterize land surfaces quantitatively in terms of slope gradient and curvature based upon Digital Elevation Models. It 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

Using ground survey methods will lead to the determination of spot heights which will in turn be interpolated to create the DEM. The stereoscopic photogrammetric and remote sensing raster data sources make it possible to determine heights of each cell of the DEM directly as most points on the imagery have their own heights directly determinable. In this case then the elevation of each cell is determined theoretically by aggregating of all the heights possible in each cell and not by interpolation of values of discrete points, which is based on assumption of consistent grade between two points of know elevations. However the raster data sources have their own accuracy issues and will definitely affect the accuracy of the DEM derivative.

As has already been noted ground survey methods produce only heights of spots. However the ground survey methods produce highly accurate elevations to millimeter level, which may then be interpolated. 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.

The accuracy of the interpolated values will be dependent on how smooth or rough the terrain is and how dense the data for the interpolation that is available. Smooth running topographies are ideal to produce elevations consistent with the true ground values, while rough topographies are less likely to fit the basic assumptions for interpolation.

On the other hand image data methods provide elevations that cover each point in the entire area. However the accuracies of the DEM determined from these images will be a function of the accuracy of the elevation of the images which could range from 2m to over 15m. 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

Photographic methods may be used to record images of existing water bodies. However the need to identify drainage routes which may not remain charged all-round the year has also been noted for effective urban planning and monitoring, for drainage designs and studies of sediment transportation and erosions etc. One area where the use of Digital Elevation Models has proved very efficient is in the delineation of drainage and catchment features of the terrain.

The catchment or the drainage basin has been recognized as the most significant surface unit in the studies of the environment. The introduction of the Digital Elevation Model has radically changed the labourious processes of the traditional catchment boundaries delineation which have been manually derived from topographic maps, (Bertolo, 2000). Conventional delineation of drainage features on topographic maps, were located by examining the contour lines. Naturally in such cases arrows were drawn perpendicular to each contour, in the direction of the steepest descent to show runoff flow direction. With recent advances in computer simulation, drainage areas can now be marked out automatically using Digital Elevation Models (DEM) of the area of interest. The value of each cell of the DEM represents the elevation of the land surface. The drainage cells are determined by confirming how water flows, that is the steepest descent from one cell to one of the immediate surrounding cells, until the cell at the outlet point location is found (Maidment, 2002).

Geographic Information Systems have the capacity to delineate and describe drainage routes when a Digital Elevation Model (DEM) is developed using topographic data. Lo *et al*, (2002) has suggested that the "hydrological approach" proposed by Mark (1984) is the more commonly used method of the drainage area delineation. In this method, the number of cells in the grid DEM that drain into each cell of the grid DEM is determined by checking the steepest descent from a cell to the ones immediately surrounding it. At this stage the aim is to count how many cells will cumulatively drain into each of the cells of grid. Fig. 3 illustrates the scheme. Fig 3.1a is a DEM which direction of steepest descent is shown in Fig. 3.1b. This process results in a matrix, called the "drainage area transform" (Fig. 3.1c), where each cell is populated by the number of cells that cumulatively drain into it. The information in the drainage area transform is then used to trace the "channel pixels," as identified by those grids with large drainage accumulations. All the cells in the drainage transform that have values that exceed a minimum channel identifying threshold are marked in Fig. 3.1d.

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

From a), DEM, Finding direction of flow

from one grid to another subject to steepness of slope in Flow Direction diagram, b)

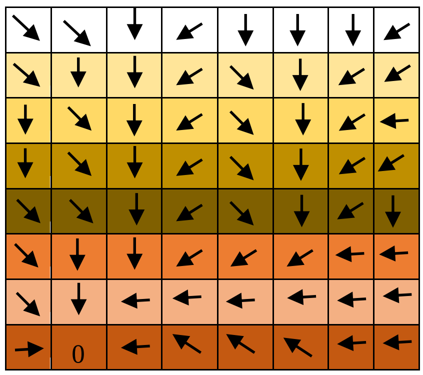

Fig. 3.1b Flow Direction diagram

Fig. 3.1a DEM with elevation values

From b), Flow Direction diagram, determining the accumulation of flow in each cell in the slope in c)

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

Fig. 3.1c Drainage area transform

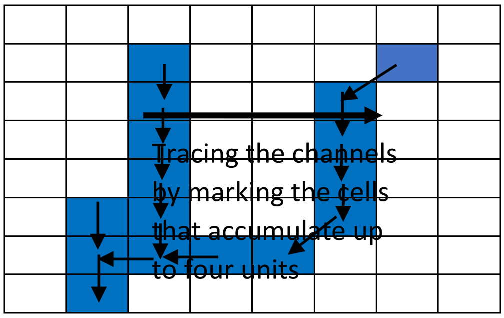

Fig. 3.1d Resulting Drainage Network

Fig. 3.1 Concept of the "hydrological approach" of delineating drainage network from a DEM

The channels so delineated may be non-continuous. It is necessary to carry out an interpolation process to connect the broken line segments into a properly connected drainage network. On the other hand, if the channels consist of multiple adjacent lines, a thinning process is required to turn them into continuous lines of one grid width.

The scheme of the process of the delineation of the drainage routes and sub-catchments is presented in the flow chart in Fig. 4

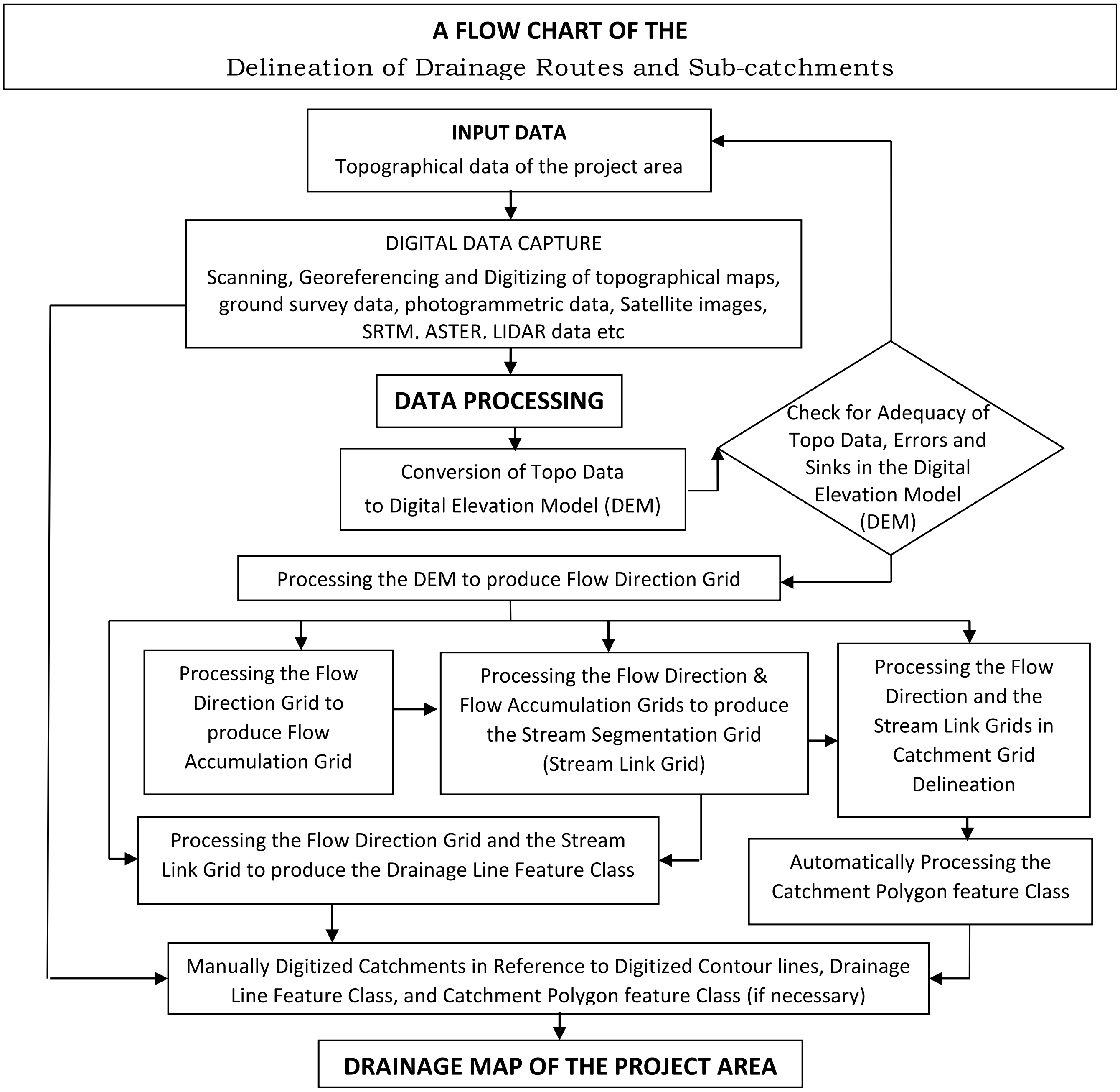

Fig. 4 Flow Chart of the DEM based delineation of drainage routes and sub-catchments

4. SURVEYOR - EDUCATION ISSUES FOR DEM DEVELOPMENT

Training curricula of Colleges and Universities in the developing world are reviewed relatively slowly. As is obvious today there appears not to be a structured interest in the development of curricula that equips 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.

Kreveld (1996) suggests 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.

5. CONCLUSION

It is obvious that the Digital Elevation Model 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.

It is important to note that advances in computational geometry may not be sustainable without the active participation 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.

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Dr. Akajiaku Chukwunyere Chukwuocha hails from Itu Ezinihitte Mbaise, Imo State Nigeria. He is a thorough bread Surveyor and a clergyman of the Anglican Diocese of Owerri, Nigeria. He is presently the Administrator and Vicar of the Cathedral Church of the Transfiguration of our Lord, Owerri. Dr. Chukwuocha holds a Ph.D. in Surveying and Geoinformatics from Nnamdi Azikiwe University Awka, Nigeria, M.Sc Geoinformatics and Surveying, University of Nigeria, Nsukka, B.Sc. (Hons.) Surveying and Photogrammetry, Enugu State University of Science and Technology Enugu, and Diploma in Land Surveying from the Federal Polytechnic, Nekede Owerri.

Dr. A. C. Chukwuocha is a member of faculty of the Federal University of Technology, Owerri, Nigeria. His research interests span Global Navigational Satellite Systems (GNSS), Geographic Information Systems (GIS) and Geodesy. He is a Registered Surveyor with the Surveyors Council of Nigeria (SURCON), a full member of the Nigerian Institution of Surveyors (NIS). He is a member of the National Association of Geodesy (NAG) of Nigeria, a member of the National Union of Radio and Planetary Sciences (NURPS).

Dr, Chukwuocha has a very wide field of experience in the Surveying Industry. From the time of graduation he has worked with the Owerri Capital Development Authority, Owerri Nigeria with leadership responsibilities in urban development design, monitoring and control. He later worked in the Oil mineral exploration industry in the Niger Delta region of Nigeria with the American Western Geophysical Company, and the French Compagnie General De Geophysique (CGG). Dr. Chukwuocha who played very important roles in the development control of the present Owerri Capital Territory of Imo State Nigeria by spearheading the densification of survey controls across the capital territory from the late 1980s to the mid-1990s still has interest in control densification using electronic methods.

He has published a number of works in Surveying and Geoinformatics including his Ph,D, research on “GIS – Based Approach to Urban Drainage Network Design” (2012), “Delineation and Characterization of Sub-catchments of Owerri, South East Nigeria” – American Journal of Geographic Information System, 2014, 3(1), pp. 1-9; GIS Based Mapping of Natural Drainage Routes of Owerri, South East Nigeria, - International Journal of Current Research, India. (Accepted 2013); “Modern Trends in Topographic Data Collation for Environmental Studies and Engineering, Journal of Environmental Design and Technology, Owerri. Vol. 1 (3). 2012., “GIS – Based Urban Planning and Monitoring Best Practices for

West Africa" African Journal of Environmental Science and Technology, vol. 8(1), 2014, among others.

Dr. Chukwuocha also authored the book, "The War Within", published in 2009 under the Hippo Titles of Zondervan publishers, Grand Rapids, MI, U.S.A. The book which explores the Christians quest to live up to the call to perfection in Christ may still be his most outstanding work.

BIBLIOGRAPHICAL NOTES - MRS. NGOZI B. AC-CHUKWUOCHA

Mrs. Ngozi Blessing AC-Chukwuocha holds a Diploma in Quantity Surveying from the Federal Polytechnic, Nekede Owerri, B.Sc. (Hons.) Estate Management, Enugu State University of Science and Technology Enugu, M.Sc in Environmental Management, Enugu State University of Science and Technology Enugu. She is currently a Ph.D. candidate at the Rivers State University of Science and Technology, Port Harcourt, Nigeria.

Mrs. AC-Chukwuocha is a Registered Environmental Specialist with the National Registry of Environmental Professionals, U.S.A. She is a member of the Nigeria Environmental Society (NES). She has published quite a number of works including, "Trace metal availability in soils of watershed in relation to land use in Owerri, South East Nigeria" Journal of Science and Sustainability (NREP), 2011, "A Comparative Analysis of emission of methane from live stock farms in Enugu, South East Nigeria", Journal of Agricultural Science and Technology, 2011, "Physio-chemical gradient and in-situ yield in pelagial primary production of the middle reaches of Imo River in Etche, South East Nigeria", Journal of Ecology and Natural Environment 2011.

Mrs AC-Chukwuocha is a staff of the Department of Environmental Technology of the Federal University of Technology, Owerri, Nigeria. She continues to provide leadership for the women of the Cathedral Church of the Transfiguration of Our Lord, Owerri, Nigeria, where she serves as the Vice President of the Women Ministries of the Church. She is an avid lover of people and keeps working in every way to improve the quality of their lives.

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