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UofKEJ Vol. 1 Issue 1 pp. 32-40 (June 2011)

UNIVERSITY OF KHARTOUM ENGINEERING JOURNAL (UOFKEJ)

Quality Assessment of DEMs Derived from 1:100,000 Scale Topographic Maps

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Abstract: This paper presents the output of a research work undertaken to assess the quality of digital elevation models (DEMs) derived from the 1:100,000 scale topographic maps produced by the Sudan National Survey Department and British Ordnance Survey in 1970's/ 1980's. Despite the increasing concern for understanding and working with errors existing in DEMs, knowledge about DEM quality is still at an early stage, especially in the developing countries. This paper presents the results of the accuracy tests which were performed for different types of topography. The overall TOPOMAP-DEM RMSE was found to be about ±7.066 m. A key outcome of this research is a mathematical model for TOPOMAP-DEM contours quality assessment and a defined procedure for producing a comprehensive DEM quality report. Also it provides the knowledge and the means for incorporating considerations of DEM quality. Additionally, it revealed the possibility of producing DEMs from topographic maps, with reasonable accuracy, using appropriate and unsophisticated interpolation methods such as the natural neighbour (NN) interpolator.

Keywords: Topographic map; Digital elevation model; Cartographic quality; Root mean square error.

INTRODUCTION

People live on Earth and learn to cope with its terrain. Topographic scientists are concerned with measuring and describing its surface and presenting it in different ways, for example, using maps, ortho-images, perspective views, etc. The civil engineers design and construct buildings on it; geologists try to study its underlying construction; geomorphologists are interested in its shape and the processes by which the landscape was formed. Despite these differences in emphasis and interests, these specialists have a common interest, that is, they want the surface of the terrain to be represented conveniently and with good or reasonable accuracy to fulfil at least the minimum required specifications. Information about terrain surface plays a key role in nearly all environmental research and applications including hydrology, geomorphology, ecology, and other disciplines [1].

Geospatial data, also known as geographic data, lie at the heart of any GIS. Geospatial data describes the location and characteristics of earth surface features and phenomena. A digital elevation model (DEM) is a type of geospatial data set, which describes the elevation of the land surface. The height and form of terrain has a fundamental influence on most environmental phenomena. Consequently, DEMs are widely used in environmental applications [2].

Geospatial analysis is a suite of methods that can be applied to transform geospatial data into information describing geospatial patterns, geospatial relationships and spatial processes.

Geospatial modeling is an application of a series of spatial analysis techniques, which together lead to the derivation of new geospatial data representing earth surface phenomena. Geospatial modeling often achieves only limited success due to the quality of source data. Digital elevation data and other spatial data sets are inevitably contaminated with some type of error whether it is gross, systematic or random. Users of DEMs should be urged to appraise the quality of their elevation data and derived digital elevation models [3]. Data sets derived from DEMs have been found to be very sensitive to the quality of DEM [4]. Therefore, having made a DEM quality assessment, the user needs to consider the influence of DEM quality on derived products and models [5]. Despite the increasing concern for understanding and working with the uncertainty within DEMs, knowledge about the DEMs error is still at an early stage, particularly in the developing countries. This is due to the fact that most users of DEMs have poor knowledge about the quality of DEMs and its impacts on the derived products.

In some developed countries (e.g. United State of America, Canada, Japan, Sweden) revised and up-to-date maps at small scales are continuously produced using current elevation data captured by remote sensing devices. In developing countries, Governmental Mapping Corporations and private mapping firms are lagging far away to produce fresh topographic maps or even to revise the existing ones at regular time intervals. This dim status is due to poverty, inadequate technical capacities in the area of geo-information and lack of knowledge about the importance and role of topographic maps and digital elevation models (DEMs) in the local and national development. Taking Sudan as an example, only 200 topographic map (1:100,000) sheets out of 920 for the full coverage of the country at this scale have been produced to cover selected areas. In addition, up to now no endeavors have been made by any Sudanese mapping corporation or firm to generate digital elevation models for Sudan. Unfortunately, the process of extracting topographical information from existing topographical maps and integrating them in a new digital topographical map is usually a lengthy and time consuming process. This is due to the differences in map units and contour intervals between the existing base maps and the new ones.

The major objectives of this research can be summarized as follows:

- Determine the relative accuracies of the TOPOMAP-digital elevation model data for defined study sites versus higher accuracy elevation data at the same site.
- Evaluate the impact of topography on the accuracy of TOPOMAP- DEM's Quality.
- Assessment of the Cartographic quality of the contour lines drawn from the TOPO-MAP DEMs.

In this paper, a framework has been prepared for the accuracy assessment of DEMs derived from 1:100,000 scale topographical maps. Quantitative statistical tests were performed on the elevation data extracted from contour lines. These tests were based on control points presented in the topographic maps and used as reference elevation data sets. The number of control points used for each study area was presented in Table 1. These control points were randomly distributed throughout the study areas. Fig. 1 shows the distribution of control points of Habilla study area as obtained from topographic maps at scale 1:100,000.

Table 1. Control points used as reference elevation data set for each study site

Study area	Number of control points
Abu Guta	83
Almaseed	73
Almanagil	41
Khartoum	167
Omdurman	169
Jabal Awlya	65
Rufaa	75
Habilla	188

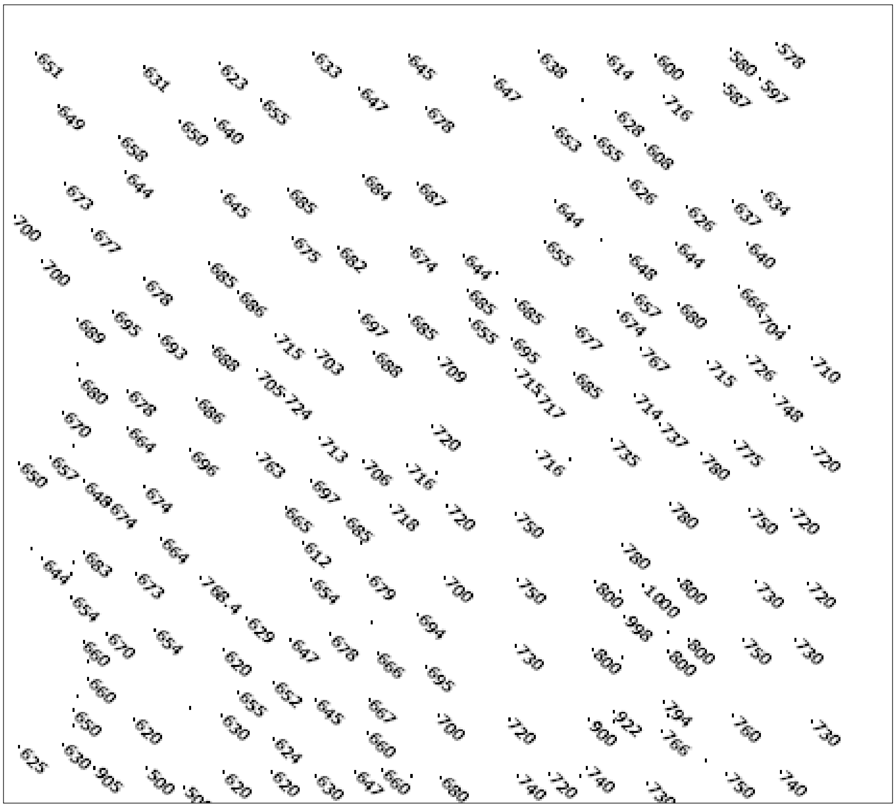

Fig. 1. Distribution of reference control points (Habilla study area)

Table 2. Topographic maps at scale 1:100,000

Map Name	Sheet no.	Date	Lat. Min. (Deg) N	Lat. Max. (Deg) N	Long. Min. (Deg) E	Long. Max. (Deg) E	Min. elev. (m)	Max. Elev. (m)	Elev. Rang (m)	Terrain description
Abu Guta	418	1989	14.5	15	32.5	33	376	449	73	Flat
Almaseed	388	1975	15	15.5	32.5	33	364	415	51	Flat
Almanagil	448	1988	14	14.5	32.5	33	380	437	57	Flat
Khartoum	359	1975	15.5	16	32.5	33	358	527	169	Gentle lope
Omdurman	358	1975	15.5	16	32	32.5	374	519	145	Gentle slope
Jabal Awlya	387	1975	15	15.5	32	32.5	373	498	125	Gentle slope
Rufaa	449	1975	14.5	15	33	33.5	378	563	185	Gentle slope
Habilla	590	1990	11.5	12	30	30.5	500	1200	700	Steep slope

2. MATERIALS AND METHODS

2.1 Study Area

The study area is 23,328 Sq.km and is composed of eight equal area sites (2916 Sq. km). These sites are scattered over an area bounded by latitudes 11.5º N and 16 º N and longitudes 32º E and 33.5º E. Each site is covered by only one map sheet at scale 1:100,000. The terrain complexity in these sites varies from flat terrain to deep steep terrain. The terrain elevations range between 358 m to 1200 m, with an elevation difference ranging between 51 m to 700 m. The terrain characteristics of the different sites are presented in Table 2.

2.2 Methodology

The methodology adopted in conducting this research work can be summarized in the following:

(i) Data collection
(ii) Determination of the relative vertical accuracy of TOPOMAP-DEM
(iii) Assessment of the cartographic quality of the contour lines drawn from TOPOMAP-DEM

2.3 Data Collection

For data collection, firstly, all topographic-map sheets were scanned and saved as images. Secondly, scanned topographic map sheets were converted into a form appropriate for the test. This step was executed by using on-screen digitization of all contour lines and tags their elevation values on the corresponding attribute table which was automatically generated while digitizing contour lines. Digitized contour lines were converted into points and their corresponding horizontal coordinates were added using the add XY tool available in ArcGIS 9.2 software. The converted points were used to generate DEM using "Natural Neighbour" interpolation method. This interpolation method was used in the study, because of its good performance when elevation data sets were extracted from contour lines. This is due to the fact that the density of elevation data is high along contour lines whereas there were no elevation data sets between contour lines (biased distribution). The same procedure was implemented for converting all of the reference elevation data sets into digital form, except the step of interpolation.

2.4 Determination of the Relative Vertical Accuracy of TOPOMAP- DEM

The present study focuses on the vertical accuracy of TOPOMAP-DEM elevation data covering all study areas. Determining the vertical accuracy of TOPOMAP-DEM elevation data essentially involves carrying out statistical computations of the elevations differences between TOPOMAP-DEM and a reference data set which was extracted from the 1:100,000 topographic map sheets. This step has been executed by overlying the reference data set and TOPOMAP-DEM, then using subtract tool available in ArcGIS 9.2 software to apply subtraction operation on the two sets of data. This operation was carried out in pixel by pixel mode. The result of this operation was a data base table of errors or differences in elevation between TOPOMAP-DEM and reference data which could be exported to Microsoft Excel to perform the statistical analysis. To perform the statistical analysis, small program has been set, due to the fact that some statistical parameters (root mean square error, average absolute error) can't be computed directly by the built-in scripts or programs available in excel worksheets. The results of the computation and statistical analysis were summarized in Table 3. Table 3 was obtained using Eq. (1), (2) and (3) below:

$$Average\ error = \frac{\sum V}{N} \quad (1)$$

$$Average\ absolute\ error = \frac{\sum |V|}{N} \quad (2)$$

$$Root\ mean\ square\ error\ (RMSE) = \sqrt{\frac{\sum V^2}{N}} \quad (3)$$

For further accuracy assessment, error frequency distribution histograms were drawn and presented in Figs. 2-9.

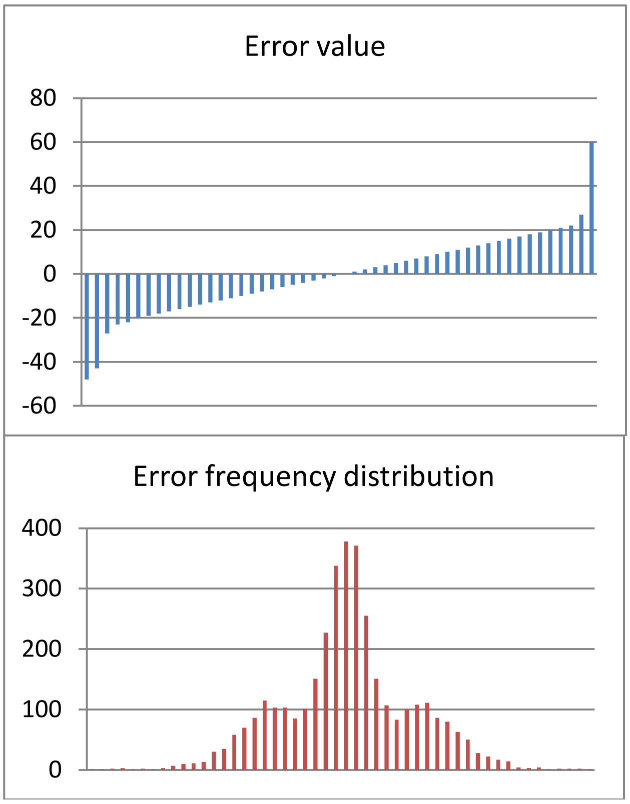

Fig. 2. Errors histogram of TOPOMAP-DEM (Abugota study area)

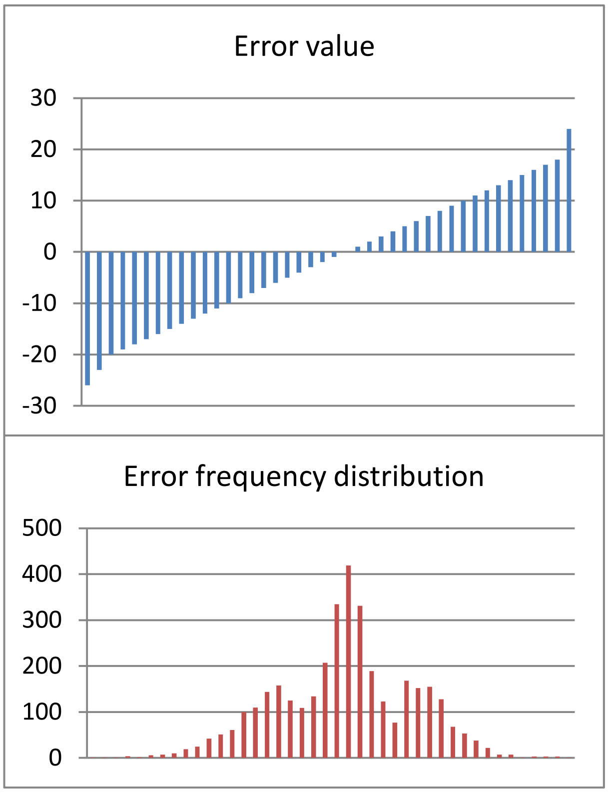

Fig. 4. Errors histogram of TOPOMAP-DEM (Almanagil study area)

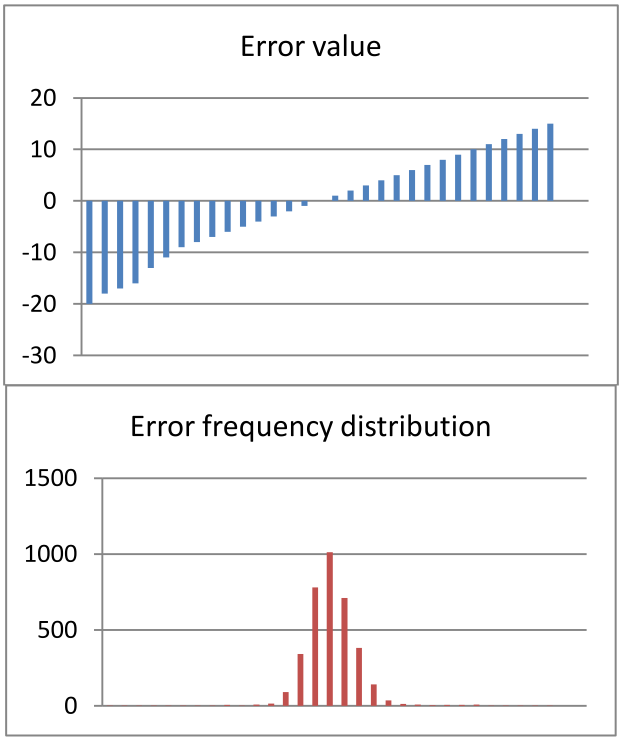

Fig. 3. Errors histogram of TOPOMAP-DEM (Almaseed study area)

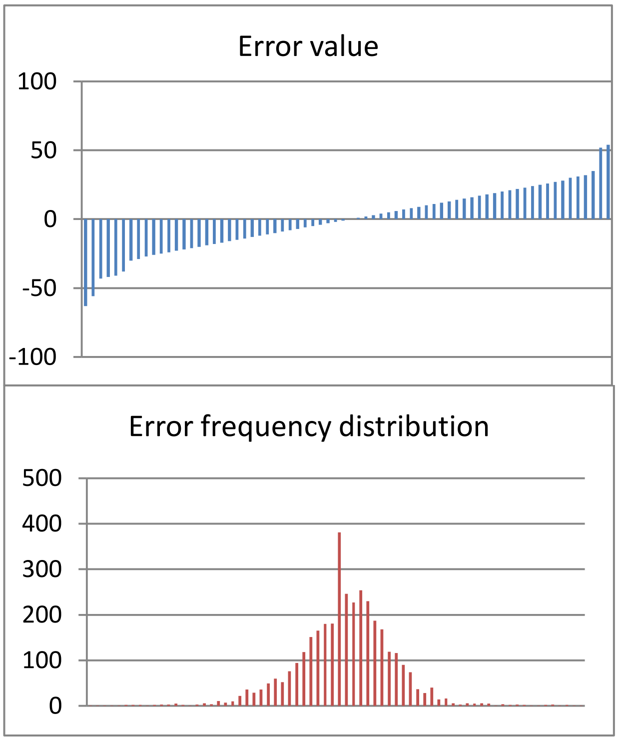

Fig. 5. Errors histogram of TOPOMAP-DEM (Jabal Awlya study area)

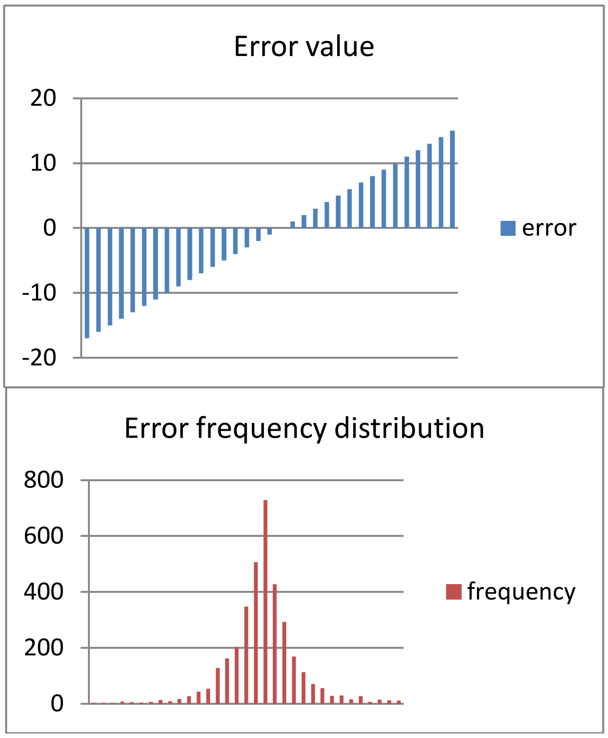

Fig. 6. Errors histogram of TOPOMAP-DEM (Khartoum study area)

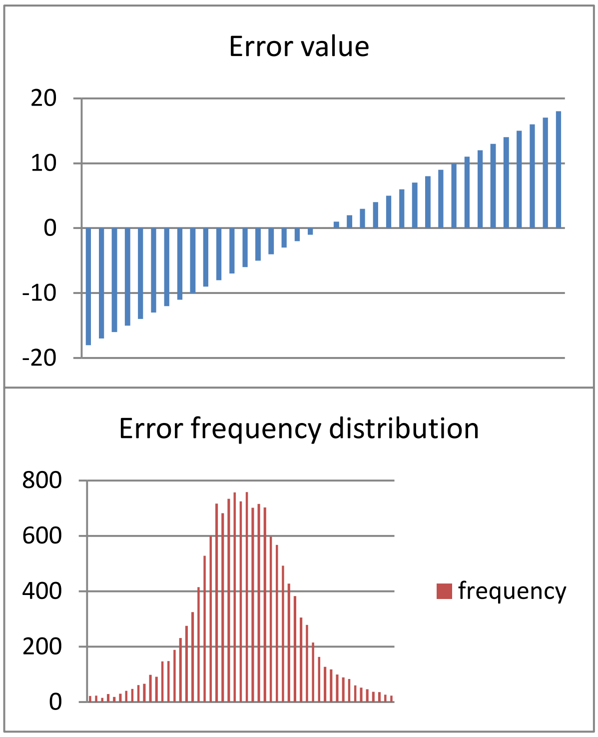

Fig. 8. Errors histogram of TOPOMAP-DEM (Rufaa study area)

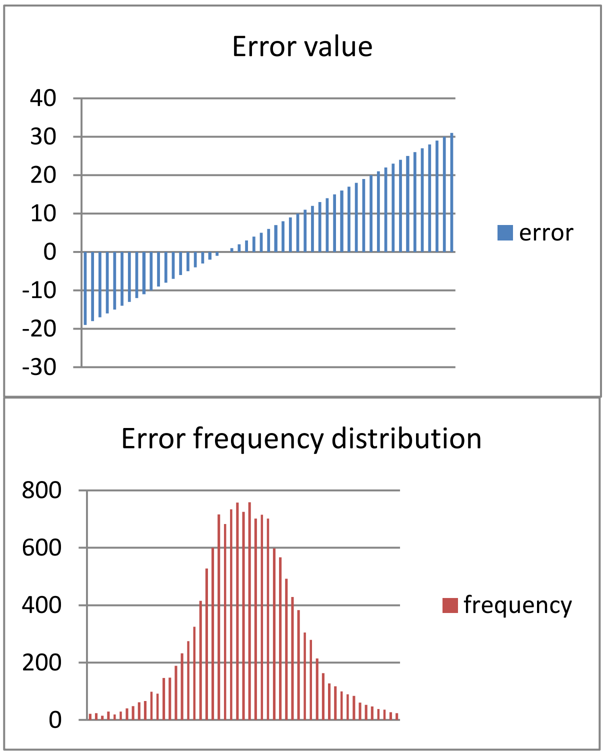

Fig. 7. Errors histogram of TOPO-MAP-DEM (Omdurman study area)

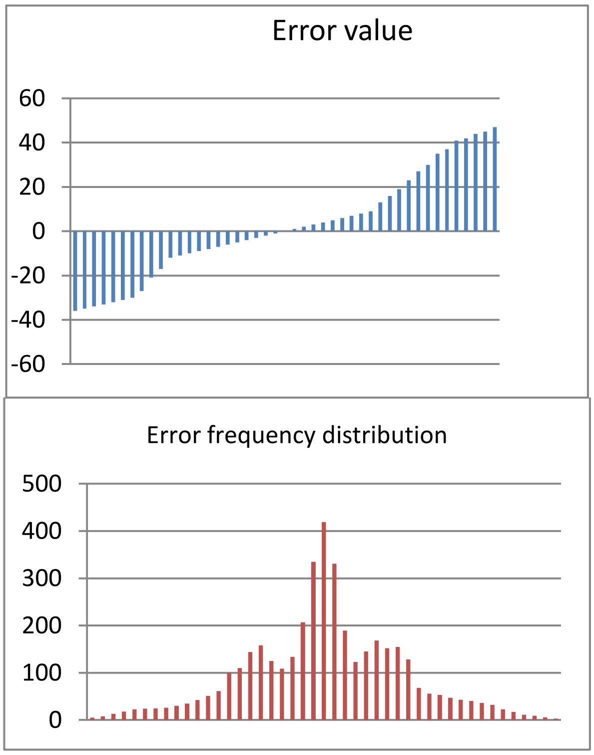

Fig. 9. Errors histogram of TOPOMAP-DEM (Habilla study area)

Table 3. Study areas digital elevation model errors

Study Area	Max. error(-) (m)	Max. error(+) (m)	Average Error (m)	Av. abs. error (m)	RMSE (m)
Abu-Guta	-15	14	-4.231	4.730	±4.474
Almaseed	-13	15	-1.873	2.581	± 2.665
Almanagil	-12	19	-1.321	2.335	±3.430
Khartoum	-15	13	0.547	2.769	±4.136
Omdurman	-17	18	0.613	5.613	± 9.716
Jabal-Awlya	-18	20.5	-0.005	6.187	± 7.648
Rufaa	-12	14.5	-0.022	2.613	± 4.104
Habilla	-36	47	-9.525	15.338	±16.954

Table 4. Summary results for all study areas

Source data	Overall Average abs. error(m)	Overall RMSE (m)	Reference data
TOPO-MAP	5.481	±7.066	Cont. points

2.5 Assessment of the Cartographic Quality of the Contour Lines Drawn from TOPOMAP-DEM

One of the major objectives of this study is the assessment of the cartographic quality of contour lines drawn from TOPOMAP-DEM. As cited by many researchers, TOPOMAP-DEM elevation data is contaminated with various types of gross, systematic and random errors. These errors will definitely affect the quality of TOPOMAP-DEM and its derivatives such as slope, aspect and contours. To investigate the cartographic quality of contour lines, the following steps were taken:

- Interpolating contours directly from the generated TOPOMAP-DEM.
- Comparing interpolated contours with their corresponding original contours presented in 1:100,000 topographic maps.

The goal of the first step was to carry out a visual assessment of the cartographic quality of contours interpolated from the TOPOMAP-DEM. To this end, the contour interpolation tool available in ArcGIS 9.2 was used to create a vector contour map with a vertical interval value of 10 m / 20 m. The goal of the second step could also be achieved by superimposing the resultant interpolated contour lines over the original contours using ArcGIS 9.2 tools as presented in Fig. 10-12

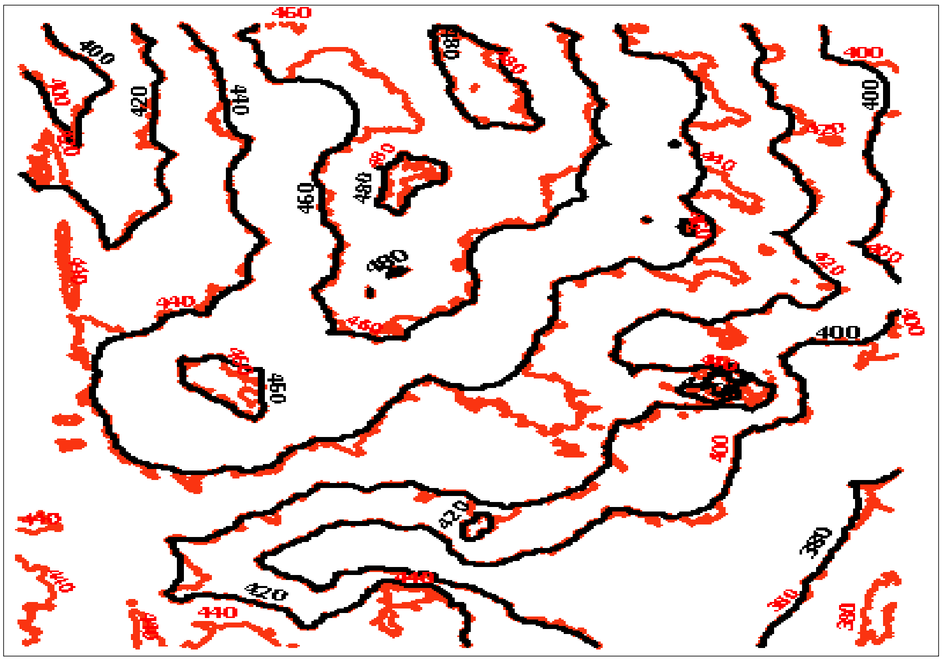

Fig. 10. DEM- contour map versus original contour map (Omdurman)

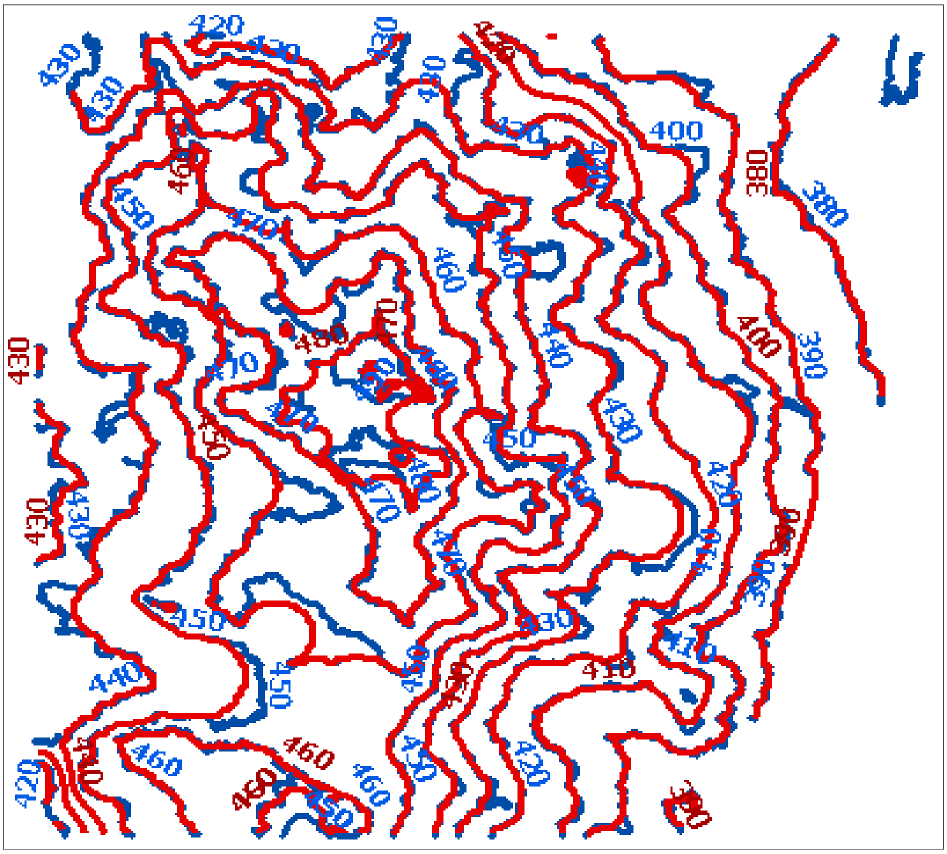

Fig. 11. DEM- contour map versus original contour map (Jabal Awlya)

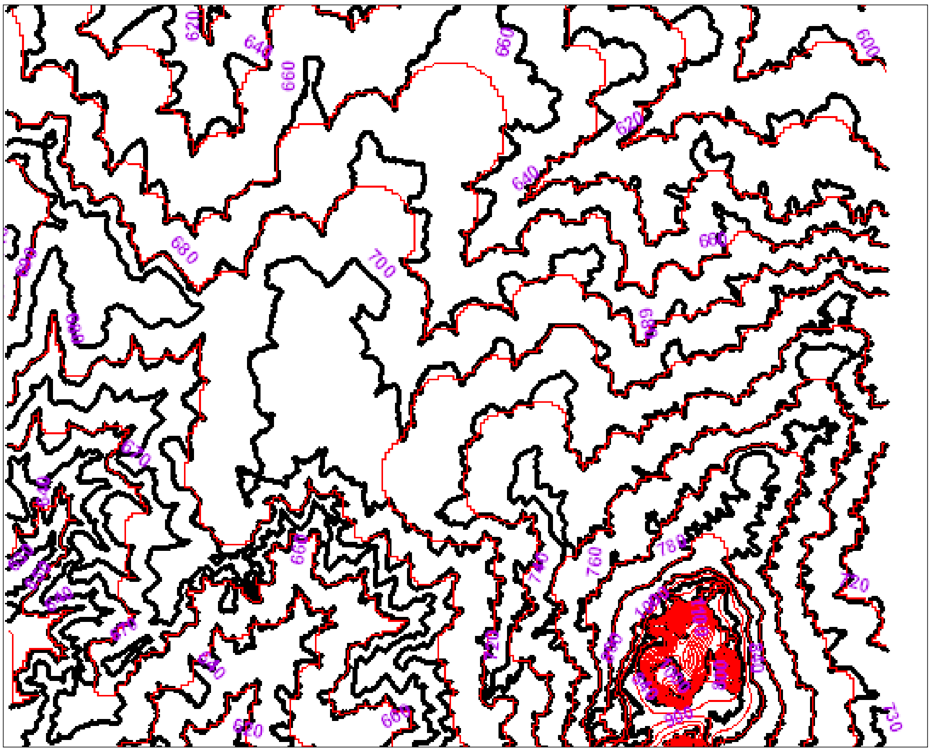

Fig. 12. DEM- contour map versus original contour map (Habilla)

3. RESULTS AND DISCUSSION

The various tests carried out in this study were meant to assess the accuracy of the DEM derived from the contour lines presented in the 1:100,000 scale topographic maps. Results of accuracy estimates presented in Table 3 showed that the TOPOMAP-DEM accuracy depends on the type of the terrain. Referring to Table 2 and 3, best R.M.S.E values ± 4.474 m, ± 2.665 m, ± 3.430 m, ± 4.136 m and ± 4.104 m were encountered in Abu Guta, Almaseed, ALmanagil, Khartoum and Rufaa study areas, respectively. The average RMSE value for the five study areas was noted to be ± 3.762 m.

The second important results were obtained in the gentle slope terrain areas (Omdurman and Jabal Awlya) with an average root mean square error value of ± 8.682 m. The result obtained in the steep terrain area (Habilla) has an RMSE value of ± 16.954 m. This RMSE value is of low accuracy compared with the results of the areas under investigation. The magnitudes of the maximum positive and negative errors recorded for all of the tested areas suggest that there were no systematic errors in the tested data sets. This was confirmed by the error frequency distribution graphs produced for all the areas under investigation. The errors frequency was likely of normal distribution as represented by histograms in Figs. 2-9. These graphs also, confirmed the low frequency of the maximum errors (< 1.5 %) for the tested areas except that for Habilla. This is mainly due to the complexity of the terrain in Habilla.

The overall average absolute error (AAE) and overall root mean square error (RMSE) values obtained for all of the study areas are 5.481 m and ± 7.066 m, respectively (see Table 4). Relating these values to the accuracy standards of the topographical map contours, a general yard stick could be used for the assessment of the quality of the TOPOMAP-DEM generated from contours. The general topographic maps standard state that, the contours vertical accuracy tolerance should be within half the contour interval of the map. Assessing the vertical tolerance between topographic map contours and the TOPOMAP-DEM contours ranges between AAE and ARMSE values i.e. between 5.481 m and 7.066 m.

Accordingly, vertical accuracy tolerance of the TOPOMAP-DEM contours should be in the range half the contour interval +5.481 — half the contour interval +7.066 m. this could be equated as follows:

$$Y = C_0 + X \quad (4)$$

where, Y = vertical accuracy tolerance of the TOPOMAP-EM contours (m), X = vertical accuracy tolerance of the TOPOMAP contours (m) and, C_0 = A factor that ranges between 5.481 —7.066 for the 1:100,000 scale TOPOMAP data. However, a refined C_0 factor could be obtained by relating the RMSE values to the elevation range (ER) values for the different study sites. A C_0 factor value for each study area was obtained by applying Eq. (5).

$$C_0 = \frac{RMSE}{ER} \quad (5)$$

The results obtained by applying Eq. (5) for the different study sites are presented in Table 5. Graphical representations of the relationship between the RMSE and the ER, and between the C_0 factor and the elevation range (ER) are presented in Figs. 13 and 14, respectively.

Fig. 13 revealed a clear linear relationship between the RMSE values and the elevation range in two elevation range zones. The first zone extends between zero and 155 m elevation range values, with a RMSE value ranges from 2.665 to 9,716 m. The second zone extends from 169 to 700 m elevation range values with a RMSE value range between 4.136 to 16.954 m. Similar relationship can be seen in Fig. 14, where a linear relationship exists between the elevation range and the C_0 factor. However, it is difficult to comment on the presence of the two zones in the investigated data sets. This needs a rigorous investigation involving a large amount of data sets representing different terrains with all types of terrain complexities, using a considerable topographical mapping scale. The effort made clearly revealed that a more refined C_0 factor showing the relationship between the terrain type represented by the elevation range and the expected RMSE value could be established. Hence a relationship between the contour interval, the elevation range and the TOPO-MAP scale could be detected.

Table 5. Refined C_0 factor values obtained by applying Eq. (5)

Study area	ER	RMSE	C_0 (RMSE/ER)
Almaseed	51	2.665	0.05225490
Almanagil	57	3.430	0.06017544
Abu Guta	73	4.474	0.06128767
Jabal Awlya	125	7.648	0.06118400
Omdurman	155	9.716	0.06268387
Khartoum	169	4.136	0.02447337
Rufaa	185	4.109	0.02221081
HabilLa	700	16.954	0.02422000

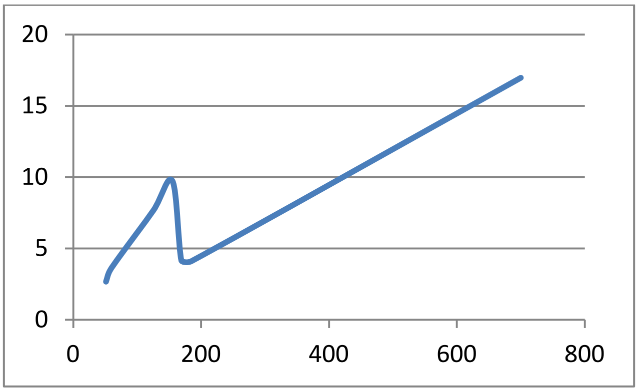

Fig. 13. RMSE versus elevation range(ER)

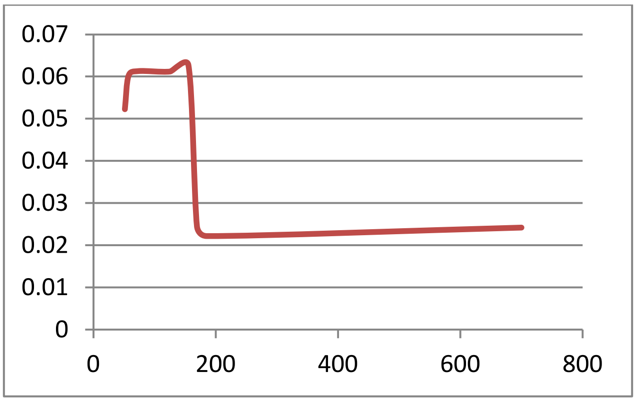

Fig. 14. C_0 versus elevation range (ER)

For further accuracy assessment, contour lines were derived from TOPOMAP-DEM elevation data sets. These contour lines were superimposed over the original contour lines presented in the 1:100,000 scale topographic maps. The results revealed that the two contour maps were generally close (see Figs. 9-11).

4. CONCLUSIONS

This study investigated the quality of the DEMs derived from elevation data sets extracted from 1:100,000 scale topographic maps covering some parts of Sudan.

The following findings were reached from this study:

1. Topography roughness has significant negative impact on the quality of DEMs generated from the elevation data extracted from contour lines in topographic maps.
2. Creation of DEMs from topographic maps, with reasonable accuracy, could be executed by using ArcGIS software tools if an appropriate interpolation method has been chosen.
3. The derived TOPOMAP-DEM contours accuracy tolerance mathematical model (Eq. 4 and 5), could be applied for the quality assessment of the TOPOMAP-DEM contours to be derived from different scales.

The following recommendations were drawn from this study:

1. It is preferable that users of DEMs should be aware of the quality of DEMs provided by commercial firms and do not use them blindly. Accordingly, some statistical tests on DEMs derived from contour lines must be carried out to assess their accuracy.
2. Users of digital elevation models should be encourage promoting their knowledge about the errors found in the generated DEMs and their effect on the derivatives extracted from DEMs.

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