Research Article

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Impact of interpolation techniques on the accuracy of large-scale digital elevation model

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Abstract: There is no doubt that the tremendous development of information technology was one of the driving factors behind the great growth of surveying and geodesy science. This has spawned modern geospatial techniques for data capturing, acquisition, and visualization tools. Digital elevation model (DEM) is the 3D depiction of continuous elevation data over the Earth's surface that is produced through many procedures such as remote sensing, photogrammetry, and land surveying. DEMs are essential for various surveying and civil engineering applications to generate topographic maps for construction projects at a scale that varies from 1:500 to 1:2,000. GIS offers a powerful tool to create a DEM with high resolution from accurate land survey measurements using interpolation methods. The aim of this research is to investigate the impact of estimation techniques on generating a reliable and accurate DEM suitable for large-scale mapping. As a part of this study, the deterministic interpolation algorithms such as ANUDEM (Topo to Raster), inverse distance weighted (IDW), and triangulated irregular network (TIN) were tested using the ArcGIS desktop for elevation data obtained from real total station readings, with different landforms to show the effect of terrain roughness, data density, and interpolation process on DEM accuracy. Furthermore, comparison and validation of each interpolator were carried out through the cross-validation method and numerous graphical

representations of the DEM. Finally, the results of the investigations showed that ANUDEM and TIN models are similar and significantly better than those attained from IDW.

Keywords: DEM, contour mapping, spatial interpolation, TIN, IDW, ANUDEM and GIS

1 Introduction

Digital elevation model (DEM) is a raster data model with the defined resolution typically used to visualize the variation of the Earth's surface to realize terrain features [1]. It can be established by gathering spot elevation measurements and then by predicting the values of points to a defined surface [2]. With reference to some criteria such as accuracy, cost, time, ease of use, and applicability, there are several sources of data for building DEM [3,4], such as airborne laser scanning, photogrammetry techniques, remote sensing, field survey, and unmanned aerial vehicle. DEM is usually the high-quality spatial data based on which many products can be derived from its analysis including contour lines (CLs), volume calculations, profile, slope, aspect, drainage networks, and so on [5].

CLs are an effective method of presenting relief, functioning in geography since the sixteenth century [6], but this is not the only and the best method for displaying the topography. In general, hypsometric maps in combination with shaded-relief maps are in common use. CLs are deemed as a final product for map edition [7]. In contrast, a topographic map, also known as a contour map, utilizes CLs that have the same elevation above the datum [8] to depict Earth's surface features [9]. A CL is an imaginary line of intersection between a level plane and a natural surface of the Earth [10]. Each contour is a closed curve either within the map boundary or outside [11]. They are useful to visualize the Earth's topography, which contains a variety of landforms or natural geographical features such as mountains, plains, hills, and rivers, which are characteristic of an area [12].

The reference elevation points acquired from different survey methods are used for generating DEMs, which are employed in many disciplines, starting from geo-information

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to civil engineering to serve as inputs for decision-making [13]. The extent and the location of a region have a great influence on the choice of the best procedure to collect the DEM data. In building and construction projects where the site is smaller than 40 hectares, the total station and the level instrument are considered as optimal surveying techniques to create the high-quality DEM [14]. Nowadays, the GPS RTK technology is the most popular, fast, and the easiest approach to obtain the DEM data with superior resolution [15]. Figure 1 shows the workflow for data acquisition used to produce DEM.

Spatial interpolation is the process of using existing measurements to define the required value of a data point [16]. It is commonly a raster operation, but it can also be done in vector data using a triangulated irregular network (TIN) surface model. In general, GIS software presents powerful analytical tools of various interpolation techniques to convert points into surface or grid data. The principle underlying spatial estimation is Tobler's first law

of geography or distance decay, which states: "Everything is related to everything else, but near things are more related than distant things." [17]. The quality of a DEM is affected by many factors that can be classified into (1) sample data density [18], (2) distribution of the source data [19], (3) data accuracy [20], (4) characteristics of the surface or terrain roughness [21], (5) cell size or spatial resolution [22], and (6) interpolation methods [23].

Hence, the extracted values from interpolated surfaces of the same data sources show some variations. Therefore, the comparative suitability of interpolation methods must be carried out to evaluate them [24]. A number of previous studies have handled the topic of choosing the DEM creation techniques [25–28], in which some of these investigations were devoted to testing the impacts of each estimation approach for a certain engineering application [29–32]. However, a few studies were performed to evaluate the accuracy of spatial interpolation methods in relation to sample density and different topography conditions over large-scale areas [33].

Figure 1: Workflow for data acquisition.

Figure 2: Flowchart of research methodology.

Accordingly, a detailed investigation is needed to compare and validate the interpolation techniques with regard to the diverse terrain features. TIN and ANUDEM algorithms became very popular and are widely used for producing DEM at the large scale. They are designed to introduce breaklines, linear feature, into surface modeling to regulate the surface behavior in respect to smoothness and continuity [34]. In this article, the performance assessment of these two deterministic interpolation methods in addition to inverse distance weighted (IDW) is addressed using the total station data in various landform types to generate a reliable and accurate DEM appropriate for construction projects at a scale that varies from 1:500 to 1:2,000. The quality analysis of the DEM surfaces is examined by the cross-validation method [35,36] and different graphical representations of the DEM. Figure 2 presents a schematic diagram for the general methodology of the framework in this research.

2 Materials and methods

As previously listed, surface modeling depends primarily on Tobler's premise using the interpolation technique, where near points generally take higher weights than far ones. However, two major sets of estimation algorithms are widely used, namely, deterministic and geostatistical.

The deterministic methods generate surfaces using observed points, but geostatistical ones from the statistical properties of the sample points [37]. The prediction process is commonly a raster operation such as ANUDEM and IDW, but it can also be done in vector data using a TIN surface model. Nevertheless, these three deterministic techniques are addressed in the present study. This section focuses on the description of the test site, dataset, interpolation methods, and validation approaches.

2.1 Study area

The test area is situated in Safita, one of the cities of Tartus governorate in Syrian Arab Republic. Safita is located 35 km northeast of Tartus, at an altitude of 380 m above the sea level. It is characterized by its very wonderful nature scenery and green high mountains, which form 73.4% of the land. The geographic position of the site under consideration lies in Safita city at midpoint about 34° 51' 30" N latitude and 36° 06' 30" E longitude and has an extent of approximately 279 hectares as shown in Figure 3. The elevation of the terrain surface in this site ranges from 217.8 to 362.3 m. In addition, a wide variety of relief landscape is included that changes from fully flat to mountainous one with steep gradients for making the area extremely in need of validation.

2.2 Dataset acquisition

Evaluation and validation have been performed through field survey using the total station with an angle accuracy of $\pm 2''$ and a distance accuracy of $\pm(2 \text{ mm} + 2 \text{ ppm})$. The collected dataset for this research consists of 4,128 test points that cover a wide spectrum of landforms in the mountainous site to analyze the topographic effects on the interpolation technique that is applied to generate DEM. The terrain features include hills, streams, ridges, etc. However, the absolute vertical accuracy of points should be at least half of the required contour interval. In contrast, the number of spot elevations per hectare is concerned with the map scale that was taken in this study as 1:2,000 and the average density of data points is 15 pts/ha.

The conformal projection adopted for mapping in Syria is double stereographic that is based on geodetic datum Clarke 1880 and has the European Petroleum Survey Group, code 22770. Therefore, all available data

Figure 3: Location of the research site.

are georeferenced according to this applied coordinate system using the ground control points (GCPs), which have uncertainty within the plottable accuracy (± 0.2 mm) at the engineering plan. The spot elevation data are imported from MS-Excel into ArcGIS 10.2 as a feature class and divided randomly into two subsets (Figure 4). The first one forms about 90% of the acquired

data, which are utilized as an input to each of the estimation methods for producing a high-resolution DEM. The second one contains the remaining 10% that is considered as checkpoints (CHPs) to validate the accuracy of the interpolated surface.

2.3 Spatial interpolation methods

With reference to the Earth's surface, the captured data can be represented in a raster or vector model [38]. The grid format data represent the landscape as a matrix of square cells. It is considered a functional surface since the z-value of any point stores single observation of the phenomenon such as elevation, pollution, and percent rainfall. The raster data model is built from spot level points to estimate the height of each cell. Spatial deterministic or statistical interpolation methods are applied to predict the value of elevation at any specific position using a weighted average of neighboring measurements [39]. The three deterministic interpolation techniques that will be addressed in this article are TIN, IDW, and ANUDEM algorithms.

2.3.1 TIN method

TIN is a procedure to originate a linearly estimated model of unknown values [40]. It is a series of adjacent triangles, which are assigned from randomly spaced nodes with 3D coordinates in accordance with a set of rules, mostly relied on Delaunay's triangulation [41,42].

Figure 4: Spatial distribution of dataset in the study area.

Figure 5: Delaunay triangulation rule.

The main property of this Delaunay method is that a circumcircle of a triangle does not include any other vertex [43] as shown in Figure 5. TIN is a very helpful technique for visualizing a continuous surface in a vector model. Actually, the idea of splitting the area into triangles goes back to Hörmann [44], who applied it to measure the terrain geometry.

2.3.2 ANUDEM (Topo to Raster)

The ANUDEM approach is an interpolation algorithm, which is included in ArcGIS under the name of Topo to Raster. This process was specifically developed by Hutchinson at the Australian National University to build a hydrologically accurate DEM that fitted a large number of sample points with a suitable shape and drainage structure [45]. It relies on an iterative finite difference estimation method to optimize the computational efficiency and ensure surface continuity [46]. The drainage enforcement technique is considered as the main characteristic of ANUDEM. Nevertheless, the input data can consist of spot heights, CLs, breaklines, sink data points, cliff lines, and lake boundaries [47,48].

2.3.3 IDW

This technique estimates the value at the unsampled location through a weighted average of a data point within a specified radius generated around each grid cell as shown in Figure 6 [49]. The cell's value of the interpolated surface is calculated as follows [50]:

Figure 6: IDW method.

$$z_g = \frac{\sum_{i=1}^n z_i w_i}{\sum_{i=1}^n w_i}, \quad w_i = \frac{1}{d_i^k}, \quad (1)$$

where z_g is the predicted value at the unsampled location, n is the number of measured points used for the interpolation, z_i is the known value, w_i is the weight, d_i is the separation distance between the grid node and the data point, and k is a smoothing parameter of the estimated surface.

2.4 Validation approaches

The popular procedure of validating the quality of sample data by determining the difference between the extracted elevations from the estimated surface and actual values that are captured in the field is “cross-validation”, which is applied to verify the performance of each interpolation process by checkpoints. The main steps of the comparative analysis of interpolation approaches are detailed in Figure 7. However, the following ways are used in this research to assess and compare the accuracy of spatial estimation algorithms:

- Computing the difference, $\Delta z_{(i)}$, between each checkpoint's height, $z_{\text{check}(i)}$, and extracted data from interpolation surface, $z_{\text{data}(i)}$, as follows [51]:

$$\Delta z_{(i)} = z_{\text{data}(i)} - z_{\text{check}(i)}. \quad (2)$$

Therefore, the error validation procedure relies on the minimum and maximum error, mean absolute error (MAE), mean relative error (MRE), root-mean-square error (RMSE), and sample standard deviation as indicated in equations (3)–(6) [52–54].

Figure 7: Schematic diagram of validation approaches.

$$MAE = \frac{1}{N} \sum_{i=1}^n |\Delta z_{(i)}| \quad (3)$$

$$MRE = \frac{1}{N} \sum_{i=1}^n \left| \frac{\Delta z_{(i)}}{z_{check(i)}} \right| \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^n (\Delta z_{(i)})^2} \quad (5)$$

$$StDev = \sqrt{\frac{1}{N-1} \sum_{i=1}^n (z_{(i)} - z_{mean})^2}, \quad (6)$$

where N is the checkpoints number and z_{mean} is the mean value of the actual elevations. MAE indicates the error limit of the extracted value, MRE presents the accuracy of the interpolated data for the actual one, and RMSE measures the goodness of fit between the actual elevations and the interpolation surface.

- Establishing a correlation scatter diagram, a quantile–quantile (Q–Q) plot, with its equation to evaluate the relationship between the estimated data and the actual elevations [55].
- Building frequency histograms of the elevation errors, between the measured values and the predicted ones at checkpoints, for each of the interpolated surface to display if they are normally distributed.
- Constructing a longitudinal-section profile in ArcGIS using the 3D Analyst point profile tool that is selected to pass through various topography conditions.
- Graphical representation of the DEM surface.

3 Results and discussion

The terrain analysis or geomorphometry is commonly applied to investigate the mathematical conceptualization of the Earth's topography for characterizing landscapes and assigning the relationships between the land surface and various natural methods and developments [56]. It is a combination of earth and computer science, mathematics, and engineering [57]. DEM is considered as the essential data most vastly input to geomorphometry. In general, DEM accuracy is related to the quality of data collection procedures [58], which consist of map scale and interpolation methods. In fact, to obtain the submeter accuracy of DEM, ground survey methods, LiDAR, and aerial photography techniques should be used, but these techniques are costly [59]. This research focuses on finding the most effective estimation procedures that are widely known for constructing a large-scale DEM using a comparative approach. The TIN, IDW, and ANUDEM algorithms were assessed to produce CLs appropriate for construction projects. It was carried out using 389 well-spread sampled points over the pilot site to quantify the amount and the propagation of error emerged by the estimation approach and the data density.

The accuracy of interpolation processes was evaluated by cross-validation as stated earlier. Table 1 summarizes the descriptive statistics of the elevation errors for TIN, IDW, and ANUDEM methods. The elevation difference in TIN interpolator oscillated between -0.880 and 0.919 m with an average of -0.018 ± 0.355 m. In the ANUDEM method, the most probable value of error in elevation was equal to -0.039 ± 0.379 m, with an upper limit of 0.937 m and a lower limit of -0.933 m. Finally, the vertical variation in the IDW technique was minimally -4.196 m and maximally 4.529 m, with a mean rate of -0.065 ± 0.969 m. The

Table 1: Results of cross-validation

Variable	TIN	ANUDEM	IDW
Min. (m)	−0.880	−0.933	−4.196
Max. (m)	0.919	0.937	4.529
Mean (m)	−0.018	−0.039	−0.065
MAE (m)	0.293	0.309	0.702
MRE	0.001	0.001	0.002
RMSE (m)	±0.018	±0.019	±0.049
StDev (m)	±0.355	±0.379	±0.969
Skewness	0.289	0.239	−0.087
Count	389	389	389

results presented in Table 1 indicate the consistency between the statistical parameters of TIN and ANUDEM algorithms such as MAE, MRE, and RMSE; furthermore,

it can be observed that the IDW model provided the largest values of error, while a low value of RMSE is needed to conclude that the estimated data are close to

Figure 8: Histogram graph of elevation differences, relevant descriptive statistics, and regression model of measured elevations versus predicted values.

the observed one. This means that TIN and ANUDEM represent the best interpolators for this case.

The skewness value presented in Table 1 is considered as a measure of the asymmetry of a set probability, but it does not clearly illustrate if the errors are normally distributed in each one of the approaches. For this reason, the histogram graph and the Q–Q plots are required to fulfill that. Figure 8 shows the histograms of the elevation errors derived from the TIN, IDW, and ANUDEM predictors. Furthermore, it depicts the Q–Q diagrams for different estimation methods to detect a deviation from the bell curve. The histograms of the three interpolation methods are symmetrical with low skewness values of +0.289, +0.239, and -0.087 for the TIN, ANUDEM, and IDW, respectively. The positive skew shows that the tail is on the right, and hence, the ANUDEM surface displays slightly better results than the TIN model, but IDW indicates unnoticeable skewness. The correlation graphs between reference elevation data and each of the interpolators (Figure 8) demonstrate that TIN and ANUDEM slightly better correlated with the reference than IDW in which the spread of the plot is increased. The linear correlation coefficients of the three interpolation methods were over 0.99, which reflects a very strong relationship between the movements of the two variables.

Consequently, it is obvious that the elevation differences are normally distributed as the Q–Q graphs also confirm this, which have the best-fit linear model. This can be attributed to a large number of checkpoints and their well distribution over the study area.

Figures 9–11 show DEMs built by ANUDEM, TIN, and IDW interpolation methods with a cell size of 1 m and CLs created at 5 m contour interval. Figure 12 presents the 3D visualization of the generated DEMs of various algorithms. The visual comparison of CLs derived from ANUEDM and TIN surfaces in Figures 9 and 10 shows that both lines are nearly coincided and have a smoother shape and contrast with the extract CLs than by the IDW DEM that display jagged and broken lines as shown in Figure 11. Moreover, in the visual data analysis shown in Figure 12, the DEMs produced by ANUDEM and TIN are the best to fit the sampled data than IDW. Generally, there are some variations in the elevation along the ridgelines of the IDW model surface, where it reveals higher than the actual height at the sunny side and lower at the shady one.

Finally, another evaluation of DEM's vertical accuracy can be achieved by comparing the longitudinal-section profiles of the three interpolation methods, which is chosen to pass through an area with varied elevations as shown in Figure 13. It is shown that these

Figure 9: CLs and DEM surface generated by the ANUDEM algorithm.

Figure 10: CLs and DEM surface produced using the TIN method.

Figure 11: CLs and DEM surface creating using the IDW interpolator method.

Figure 12: 3D visualization of DEMs.

profiles have the same trend with a slight difference between ANUDEM and TIN, but significant for IDW. This result emphasizes that the accuracy of the ANUDEM and TIN techniques is close and diverse from the IDW method.

All measures to quantify the topographic shape are in some way representative of the surface roughness [60].

Nowadays, DEM provides the most standard method to derive the desired parameters such as curvature, drainage network, slope, and aspect for managing the geomorphological process [61]. The extracted topographic parameters rely on the DEM resolution and accuracy, and hence, large-scale DEMs at a high resolution, or small cell size, are more reliable to draw out these elements [62,63]. The interpolation quality is based on the required number and distribution of the selected GCPs [20,64–66], but it is influenced by data diffusion rather than its density [23]. Although the use of high sampling data gives better accuracy, it increases the required time for calculation and analysis. Therefore, as a part of this study, the method of the Syrian surveying standard for determining the data density will be considered to control the error in the interpolated DEMs emerging from the number of captured points. This procedure is mainly based on the rule that the shortest distance between two spot elevations does not exceed 0.01 m on a map, and thus, the covered area by a single point in accordance to the denominator of map scale, M , is represented as follows:

$$A_{SP} = \pi (0.01 \times M)^2. \quad (7)$$

The minimum number of the necessary data points per hectare (pts/ha) for plain area is as follows

$$U = \frac{10,000}{A_{SP}}. \quad (8)$$

If the number of the obtained points is greater than U , the terrain surface will be classified as ruggedness, which will require extra data to be collected at each change in the slope and along the natural features such as lakes, streams, and valleys. In contrast, ref. [67] presented a statistical approach to specify the adequate number of GCPs for a DEM accuracy evaluation by adopting a confidence interval of the RMSE.

4 Conclusions

The interpolation approach plays a vital role in producing a reliable and accurate DEM surface. In fact, the best results of the prediction technique are based on the nature of terrain features, the spread of reference points, and other factors related to DEM resolution, data density, and so on. This study evaluated the performance of different interpolated surfaces using the elevation data captured from field observations. Therefore, the elevation errors between the actual values

Figure 13: Profile of the three interpolated surfaces.

and predicted ones at the location of the checkpoints were tested for normality.

The cross-validation, frequency histograms, and Q-Q plots are powerful tools to measure the goodness of a fitting technique. The statistical analysis of errors did not show any important discrepancies between the two algorithms TIN and ANUDEM, while their accuracies were very similar, which is unexpected as their estimation functions are different. In contrast, the IDW method ranks the last and provided the worst interpolated surface.

Finally, this article recommends the use of the TIN model for establishing topographic maps in this case since a linear interpolator depends on creating triangles from spot elevations without being influenced by the neighboring original data values such as the case of the ANUDEM method.

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