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Examining the Interpolation Methods Used in Forming the Digital Elevation Models

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Abstract

Today, digital elevation models and digital terrain models are used in many areas, such as Geographical Information Systems (GIS), several engineering work and management of natural resources. Digital elevation models are a general source of data for terrain analysis and 3-D applications. The slope of the land, aspect, curvature, catchment area characteristics can be determined easily by the help of digital elevation models. Therefore, besides the accurate production of digital elevation models, its fast and economical production becomes a goal. Different accuracy digital elevation model can be produced by using different interpolation methods.

In this study, the concepts of digital terrain model and digital elevation model are explained. In execution, 3-D model was created from the point set whose x, y, z coordinates were known with different interpolation techniques. The results obtained were compared and tried to determine the best method that works.

Keywords: Digital terrain model, digital elevation model, interpolation, representation of terrain surfaces.

1. Introduction

Digital Elevation Model (DEM) is being used for the digital demonstration of a topographical surface. And Digital Terrain Model (DTM) is more extensive, and it is a model enabling representation of the surface in the best manner and covering elevation values of artificial and natural significant topographical details, critical land lines and irregularly distributed critical surface points. DEM is an essential element of GIS. DEM is being used in many implementations such as visualization of land surface, finding the elevation of any point on land, and finding the slope and aspect of the land surface. Briefly the purpose of DEM is to represent a piece of earth surface digitally on computers [1, 2, 3, 4]. And interpolation is used to determine the elevation value of a point as benefiting from the known elevations of neighbouring points. There are many interpolation methods being used while forming DEM. Some of these are;

- Local Polynomial Interpolation
- Simple Linear Interpolation
- Bilinear Interpolation
- Bicubic Spline Interpolation
- Multi Surface (Multiquadric) Interpolation
- Moving Average Interpolation Method
- Natural Neighbor Interpolation
- Inverse Distance Weighting Interpolation
- The Minimum Curvature Interpolation Method
- Kriging

Each interpolation method is providing different results. In this context, selection of interpolation methods conforming to land type is required. An interpolation method providing correct results at flat lands may not provide correct result at rugged lands. The use of interpolation method providing the result that closest to the structure of land will provide more realistic and reliable results. Which method is providing more correct results, and whether the method is directly related with the land conditions should be determined [4].
An infinite number of points are required to fully define a piece of terrain. However, this is not possible in

practice. Therefore, the terrain is tried to be represented by the surface created by a certain number of points. The cluster formed by these points is called a base or sampling space. Data collection is often not possible for all the points needed. Therefore, estimation operation needs to be performed. The interpolation methods used for the estimation operation do not always give enough accurate results. In this case, it is be more appropriate to choose the interpolation method suitable for the type of the terrain. In this study, the standard deviation (root mean square error) values were compared by using the differences of the height values obtained as a result of the application made on the data set using the five selected methods. The aim of the study is to determine the interpolation method giving the best result.

There are many studies on digital terrain models and interpolation methods used in our country (Üstüntaş, 1994, Bayrak, 1996, Yanalak, 1997, Yiğit, 2003, Alkanalka, 2005, Köroğlu, 2006, Erdoğan, 2007, Ayar, 2009 etc.). In all of the studies conducted, the necessity of DTM was emphasized and it was explained that it was widely used by different disciplines.

Üstüntaş (1994), in his master's thesis, talked about digital terrain models, terrain depictions, interpolation methods. In practice, on the other hand, he examined whether the program used to display the purchased terrain numerically showed or did not show the terrain correctly and determined that the softwares gave correct results.

Bayrak (1996), in his study, compared the interpolation methods used in forming DEMs (digital elevation model), the Multiquadric and the Fragmentary Bilinear Interpolation methods. Taking the difference of the heights produced by the two methods from the values read from the map, they were subjected to tests and by comparing them with each other, he examined the advantages and disadvantages they provide against each other in the studies of forming DEMs.

Yanalak (1997) explained the interpolation methods used in DEMs. In practice, he evaluated the interpolation methods used for volume calculations for the grid size, interslice distance and critical circle radius and made suggestions.

Yiğit (2003) compared weighted mean, polynomial surfaces, multiquadric, collocation with the least squares, and Kriging methods to determine the height of the intermediate points in three different test areas whose geoid heights were determined by GPS/Nivelman method.

Alkanalka (2005) did research to produce lifelike values of missing regions of DEM data obtained by photogrammetric methods due to clouding, brightness, wearing out in satellite image by using estimation methods and to determine the most appropriate estimation method for this operation. In addition to this, after finding the most suitable estimation method, he also examined the effect of the selection of the surface curve passing interval, the importance of the number of known points left in the non-data section and area size without SYM data on the accuracy of the new values obtained.

Köroğlu (2006) examined the surface modeling and the methods developed for this, which have many applications in terms of profession. With the help of the software that includes these methods, he investigated the effects of the methods on volume calculation.

Erdogan (2007) worked on the determination of production criteria and standards, testing and optimization of these methods in terms of time, cost, accuracy and utility, according to the source data types and production methods used intensively in DEM production. In practice, he produced DEMs with image matching, and tested the accuracy of the obtained DEMs. At the same time, for some of these data, digital contour line production made by photogrammetric evaluation, and DEM was produced from digital contour lines. Optimum data collection interval and DEM accuracy were tested in DEMs.

Ayar (2009), in his study, Within the framework of the protocol signed with the General Directorate of İller Bank, examined GPS measurements within the scope of Zonguldak GPS Network Project realized by İTÜ and determined the heights with interpolation methods.

Apart from the master's and doctoral theses, there are many articles and papers on this subject. In these studies, the methods were generally compared with each other and the application results were compared. In this context, the method giving the best result was tried to be determined.

In this study, unlike the literature, by using different interpolation methods for an area whose x, y, z coordinates were determined by local measurements, the accuracy of the points found as a result of interpolation was compared in terms of root mean square error and Kriging method was proved to be the interpolation method giving the best result.

2. Digital Elevation Models and Digital Terrain Models

DTM has simply been defined as the representation of digital land. Even if Miller and Laflamme (1958) [5] had formed the original term, different alternatives had been put to use. These are Digital Elevation Model (DEM), Digital Ground Model (DGM) and Digital Terrain Elevation Model (DTEM). While DEM is extensively being used in America, DGM has been used

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by United Kingdom, and DTEM has been used by United States Geological Survey and Defense Mapping Agency [6].

In practice, these terms (DTM, DEM, DGM and DTEM) are often used synonymously. But sometimes they mean different results. There may be slight differences among these terms. Li (1990) [7] had performed a comparative analysis as follows regarding these differences:

Ground →	"the solid surface of the world"; "solid base or foundation"; "surface of the world"; "sea bottom" etc.
Height →	"vertical distance from a given reference surface"; "altitude on ground level or elevation from a recognized level, especially from sea level" etc.
Elevation →	"elevation from a given reference surface, especially from the sea"
Terrain →	"roughness indicating the natural characteristics of a country", "earth, region at a region" etc.

From these definitions, some differences among DGM, DEM and DTM start to manifest themselves. For this reason, DGM frequently has the meaning of "digital model of a solid surface". As opposite to the use of term ground, the terms elevation and altitude emphasize "measurement of objects from a datum to top". These terms don't have to state the elevation from the land surface. The meaning of land is more complex and extensive. It may include the fact of elevation. But it also covers other geographical elements and natural characteristics. For this reason, DTM is more extensive than DEM, and it includes specific land characteristics such as rivers, ridge lines etc. [8,4].

DTM is the numerical and three dimensional representation of the surface of the land. In other words, the aim is to define mathematically and numerically the surface (x, y, z) with the help of points at the appropriate frequencies known appropriately as the locations defining the surface [9].

DTM may be generalized as a set of sampling points representing the spatial distribution of different types of information on land. The explanation of this generalization in formal language may be as follows:

$$K_p = f(u_p, v_p) \quad K=1,2,3,...,m, \quad P=1,2,3,...,n \qquad \textbf{(2.1)}$$

In here, Kp is representing the information at any P location on the land. (up,vp) is the two dimensional coordinate pair of the P point. M(m≥1) is the total number of land information type. And n is the total number of sampling points. For instance, let's assume that the land type is categorized as i. type land information. Then, the DTM of this constituent is stated as follows:

$$I_p = f(u_p, v_p) \qquad P=1,2,3,...,n \qquad \textbf{(2.2)}$$

DTM is the digital demonstration of spatial distribution of one or more type of land information, and the land information is expressed with mathematical demonstration in addition to two dimensional location information. Frequently, it is referred as the two and a half dimensional representation of land information of three dimensional space.

In equation 1, when m=1 and when the land elevation exists, the result is the mathematical expression of DEM. Explicitly, DEM is the subset of DTM, and it is the most basic component of DTM [4].

2.1. Digital Terrain Modeling

The operation of formation of DTM surface is referred as Digital Terrain Modeling. Moreover, this is a mathematical modeling operation. In such an operation, the points on the land are sampled. Thus, specific observation accuracy, intensity and distribution are obtained. And then, the land surface is shown with sample point sets. As different from the sample points, if the characteristics of the locations on the digital surface are required to be obtained, interpolation is applied by forming DTM surface at sample data points. Other characteristics may be elevation value, slope and surface. Figure 1 is explaining all the operations of Digital Terrain Modeling [4].

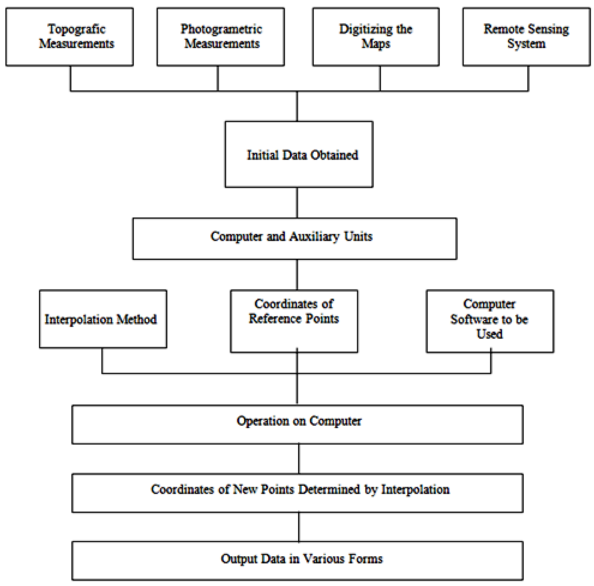

Figure 1. DTM formation process [10].

How frequent the points will be determined when the DTM is created posits an important factor. The reason is that the accuracy of digital terrain models depends on the accuracy of these points and on how frequent they express the land [9].

For the formation of DTM, points which are properly distributed on land surface and whose locations and heights are being known are required. These points are referred as "anchor points", "control points" or "reference points". New points of required frequency are generated on the model formed with the assistance of these anchor points, and the locations and elevations of these points are determined, and thus the surface is expressed as digitally. DTM has two purposes [4]:

- Calculating the elevations of points whose locations are known as benefiting from the anchor points,
- Calculating the locations of points whose elevations are known as benefiting from the anchor points.

The following conditions should be provided as much as possible while forming the DTM:

- It should be able to represent the land with the least number of anchor points.
- Land information should be processed efficiently.
- DTM should represent the topography of land with a sufficient approach.
- The operating period of the software used should be as short as possible.
- When required, numerous anchor points should be applicable as data [11,12].

Two types of methods are generally used for DTM to be done: grid and triangulation. In the grid method, the heights of the points of the network which are assumed to be placed as square or rectangular on the surface of the land are calculated. If the spots on the surface do not form a grid, interpolation between the points is made to calculate the height of the grid points [9,13]. In the triangulation method, the surface is modeled with interconnected triangles by combining the three closest points between the spots on the surface. Both methods determine the accuracy of the digital terrain model, which is based on the scale of the used map, and the surface density of these points [14,9].

DTM are used in many areas such as natural resources management, urban planning, engineering applications, disaster management, agriculture, earth sciences and military applications [9,15]. Around these days, the specialists in various discipline fields are taking office in DTM implementations. For this reason, Digital Terrain Modeling includes four main components. These are;

- Obtaining data,
- Modeling,
- Data management and
- Development of application.

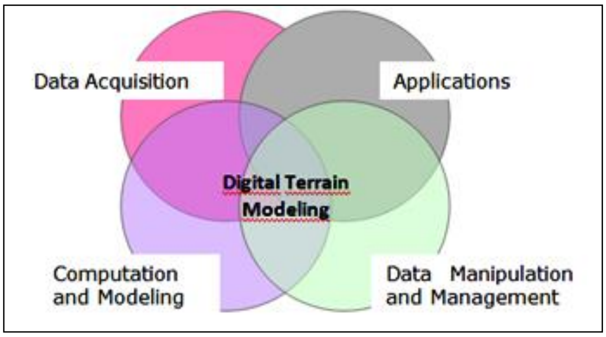

Figure 2. Quantitative Land Modeling and other disciplines [4].

3. Interpolation Techniques For Terrain Surface Models

Interpolation is an approach in mathematics and an estimation problem is statistics. And in Digital Terrain Modeling, interpolation is used to determine the elevation value of a point as benefiting from the known elevations of neighbor points. There are two implicit assumptions behind the interpolation techniques:

- The land surface is continuous and smooth.
- There is high correlation among the neighbor data points.

Interpolation is one of the basic techniques in Digital Terrain Modeling, because it is within the various phases of modeling process such as surface reconstruction, quality control, accuracy assessment, land analyses and implementations [4]. Interpolation techniques may be classified as per different criteria, and may be used for different purposes. Table 1 is showing a simple classification.

Table 1. Classification of interpolation techniques as per different criteria [4].

A Classification of Interpolation Techniques	
Criteria	**Interpolation Techniques**
Size of area for interpolation	Point based, area based
Exactness of the surface	Exact fitting, best fitting
Smoothness of the surface	Linear, nonlinear
Continuity of the surface	Step, continuous
Preciseness of the function	Precise, approximate
Certainty of the problem	Functional, stochastic
Domain of interest	Spatial, spectral
Complexity of the phenomenon	Analytical, numerical iteration

4. Materials and Methods

The implementation has been realized by using points of a section of the province of Zonguldak found with topographic measurements. The area is approximately at a size of 1 km x 1 km. The work area is

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approximately 783.550 decares, and it is rough from place to place. Implementation has been performed by using the Golden Surfer 9 program with the data set consisting of 3.180 points. When the points in data set are considered, while the highest elevation value is 652.58 m, the lowest elevation value is 531.14 m. As the result of interpolation, the standard deviation of residual values (mean square error) arising at anchor points has been calculated, and the method providing the best result at work area has been searched.

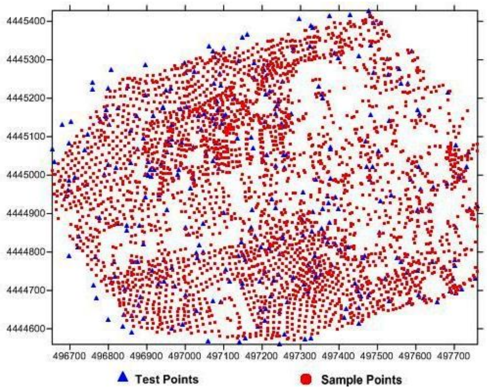

Figure 3. Distribution on land of data set where implementation will be performed.

In this study, 318 points being the 10% part of 3180 points have been allocated as test points. Test points were selected by the program to be homogeneous. Thus, there was the opportunity to make comparisons for most of the study area. With the remaining 2862 points, three dimensional digital elevation model has been formed by using different interpolation methods. The interpolation methods used in the implementation are;

- Inverse Distance Weighting Interpolation Method (IDW)
- Kriging Interpolation Method
- The Minimum Curvature Interpolation Method
- Natural Neighbor Interpolation Method
- Local Polynomial Interpolation Method

Inverse Distance Weighting Interpolation Method operates as per the principle that close points are required to affect more compared to distant ones in interpolation operation. Kriging interpolation method is operating with the variogram model as different from other methods. The Minimum Curvature Interpolation forms a trend surface such as multiquadric interpolation method. It operates with specific limit values for solution and restricts the surface. For this reason, it is being estimated that it will provide better result. Natural Neighbor Interpolation Method reaches the solution my making triangulation as different from other methods. This method is using the Delaunay triangulation. And the Local Polynomial Interpolation Method is found by separately interpolating the small areas. Within this scope, implementation had been performed on these five methods as it was considered that it would provide better result.

First, the three dimensional digital elevation model of the land had been formed with the sampling points as per the interpolation method by using the Golden Surfer 9 software. Homogeneously distributed 318 test points had been superposed on the model formed. By finding the differences among z elevation values on the surface formed by the z elevation values of the test points, m0 mean square error (standard deviation) values had been calculated.

4.1. Inverse Distance Weighting Interpolation Method (IDW)

This technique interpolates a surface according to the weighted average of the sample points, which loses weight as it moves away from the point to be interpolated [16]. General equation of the Inverse Distance Weighting Interpolation method is;

$$H_p = \frac{\sum_{i=1}^{n} h_i / d_i^2}{\sum_{i=1}^{n} [1/d_i^2]}$$

H_p: calculated elevation of point P
h_i: elevation used to calculate the height at point P
d_i: distances of the points from point P
n: number of points used in the interpolation procedure for estimating the elevation of point P

The parameters used in inverse distance weighting interpolation method, three dimensional model formed as per this method and the obtained contour line map have been shown in Figure 4.

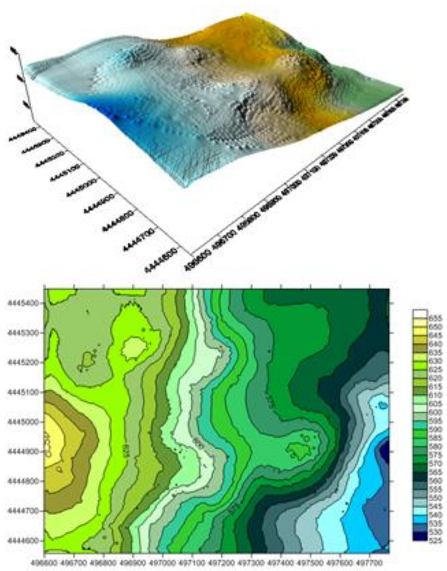

Figure 4. Contour line map formed by Inverse Distance Weighting Interpolation.

4.2. Kriging Interpolation Method

Kriging is a geostatistical method for spatial prediction. This method is defined as the best linear unbiased estimator known as collocation in mathematical geodesy (BLUP: Best Linear Unbiased Predictor) or the best linear unbiased calculator (BLUE: Best Linear Unbiased Estimator) [17]. This is used to determine the weights according to the condition that the prediction error underlying it is minimum. This is one of the great features that distinguishes the Kriging method from other methods [18,19].

General equation of the Kriging method is;

$$Np = \sum_{i=1}^{n} PiNi$$

Np: The sought value of the P point
Pi: Weight values for each Ni used in the calculation of *Np*
Ni: The undulation values of the points used in the calculation of *Np*
n: The number of points used in the calculation of *Np*.

The parameters used in Kriging interpolation method, three dimensional model formed as per this method has been shown in Figure 5.

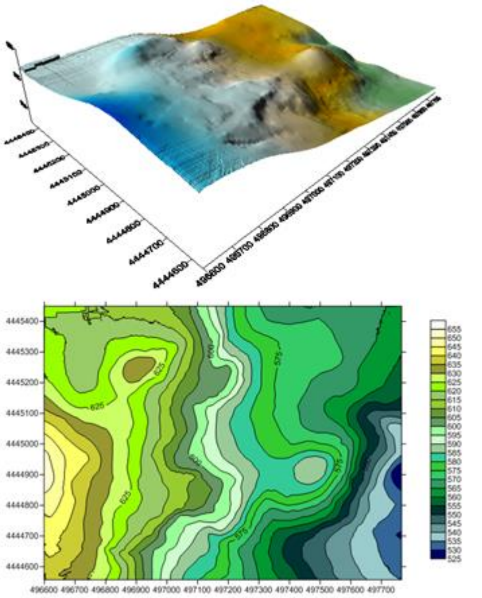

Figure 5. Contour line map formed by Kriging Interpolation Method.

4.3. The Minimum Curvature Interpolation Method

This method was developed to interpolate the heights of grid corner points so that the sum of the squares of the curvature values at grid corner points is minimum. First, the gravity values of the grid corners are interpolated and used to construct the co-gravity curves [20,21]. The parameters used in the minimum curvature interpolation method, three dimensional model formed as per this method has been shown in Figure 6.

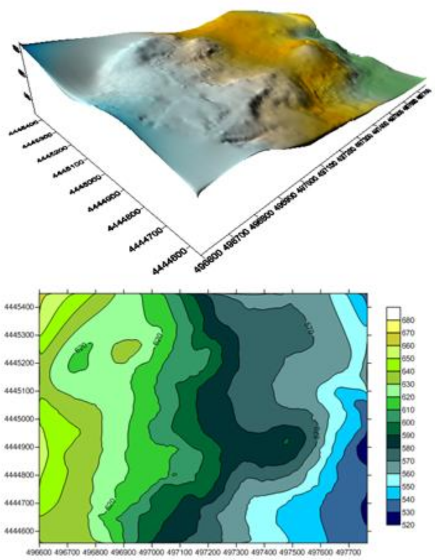

Figure 6. Contour line map formed by Minimum Curvature Interpolation Method.

4.4. Natural Neighbor Interpolation Method

The natural neighborhood interpolation method uses distance-dependent weights at sampling points while searching for interpolated points [22]. The parameters used in natural neighbor interpolation, three dimensional model formed as per this method has been shown in Figure 7.

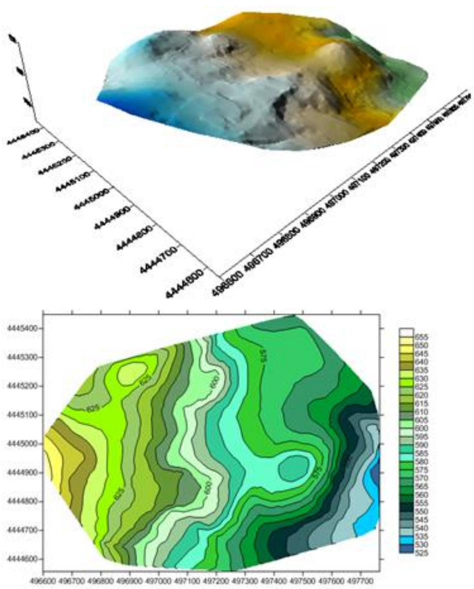

Figure 7. Contour line map formed by Natural Neighbor Interpolation Method.

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4.5. Local Polynomial Interpolation Method

The main idea of this method is to express the surface of the land with a single function [21]. General equation of the Local Polynomial Interpolation method is;

$$N(x,y) = \sum_{k=0}^{n} \sum_{\substack{j=k-i \\ i=0}}^{k} a_{ij} x^i y^j$$

x,*y*: Plane coordinates of points where we know the geoid height
a_{ij}: Polynomial coefficients
n: Polynomial degree

The parameters used in local polynomial interpolation method, three dimensional model formed as per this method has been shown in Figure 8.

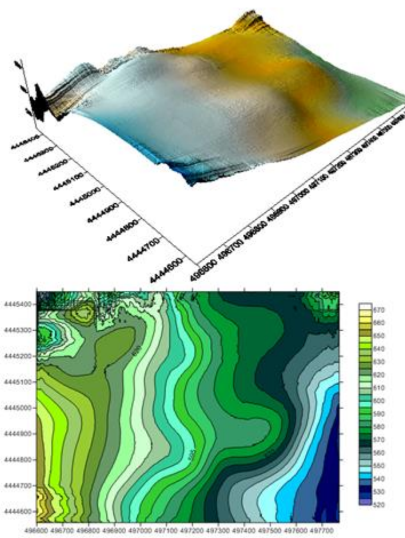

Figure 8. Contour line map formed by Local Polynomial Interpolation Method.

m_o values had been calculated by taking the differences among the z elevations of test points on quantitative elevation models found in the implementation phase.

Table 2. m_0 values calculated with the difference among known z values and z values found with interpolation.

Interpolation Method	Calculated m_0 Value (m)
1. Inverse Distance Weighting Interpolation Method	1,0725
2. Kriging Interpolation Method	0,4896
3. The Minimum Curvature Interpolation Method	0,5129
4. Natural Neighbor Interpolation Method	0,5240
5. Local Polynomial Interpolation Method	1,5452

While finding the m_0 values, first the v value had been found by taking the difference of elevation values found as the result of interpolation from the known elevation values of test points. m0 values had been obtained by placing the required values in their position in the $m_0 = \sqrt{\frac{[vv]}{n-1}}$ formula. Separate calculation had been performed for each interpolation method.

Among the methods, it had been determined that the Kriging method is the interpolation method that is representing the land surface as realistic as possible. Kriging method is consisting of more robust mathematical models. The minimum curvature interpolation addresses the surface completely. For this reason, it is providing sensitive and realistic results. It is the method that provides the best result following Kriging method.

5. Conclusion

By the interpolation methods used, three dimensional quantitative elevation models and contour line maps had been formed. When the m_0 values found as the result of implementation performed with 318 points, it being observed that the Kriging interpolation method is providing the best result. The minimum curvature interpolation and natural neighbor interpolation method are respectively following the Kriging interpolation method. Local polynomial interpolation method had provided the worst result among the methods.

As the surface is completely being addressed in the minimum curvature interpolation, it is providing results close to true. The minimum curvature method is more suitable for areas having less fracture. As interpolation had been performed for the whole surface, calculation load had been high. But by the today's computer technologies, this is no longer a difficulty.

According to the obtained results, the best estimation method had been determined as Kriging method. The most significant feature distinguishing the Kriging method from other methods is the variogram model. Kriging method has statistically and mathematically good foundations. Kriging method gives more neutral results than other interpolation methods. As the number of base points and the quality of the measure increases, the accuracy of the results will increase.

As the weight function is being taken as inversely proportional with distance in inverse distance weighting interpolation method, decreasing effects of distant points on interpolation is enabling it to provide better results than classic weighted average.

In the previously performed studies, it had been determined that the Kriging method is providing the best result among the methods used. By this study, it is proved once again that the Kriging method is the best estimation method.

In cases when the DEM data is deficient and faulty, new data with high accuracy may be obtained by using the suitable interpolation method. This condition is both economic, and ensures saving of time. Kriging method, which has a significant place in geostatistics, may also be used in geomatic engineering due to acquisition of high accuracy.

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