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Quantitative Analysis of the Digital Elevation Models Generated with IDW Algorithm of Changing Power

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ABSTRACT

This research applies quantitative analysis techniques on DEMs generated using the Inverse Distance Weighting (IDW) interpolator of different powers in order to examine the effects of the variation of the power on the accuracy of the elevations extracted from that DEMs. Real elevation data has been collected from field using ground surveying techniques with a total station instrument in a hilly corrugated terrain. DEMs have been generated from the elevation data at a unified grid cell size using IDW interpolator with varying powers starting from a power of one and ending by a power of ten. Quantitative analysis has been carried out on the DEMs using three different testing and analysis techniques; evaluation of the contour-line maps of the difference between DEMs, analyzing profiles extracted from the DEMs, then performing accuracy assessment of the extracted elevations from the DEMs using independent external checkout measurements. The analysis has shown that IDW faces difficulty in interpolating elevations in highly corrugated areas however; the interpolation operation improves with increasing the power of the IDW till the power of four. Also, at breaklines IDW with power of one faces the maximum difficulty in estimating elevations with a tendency of smoothing and approximating the DEM. Additionally, the maximum differences between profiles extracted from lower power DEMs and those from higher power DEMs have been at the corrugated parts of the terrain while at gentle terrains the profiles from different DEMs run close to each others. Finally, the accuracy of the DEM records the maximum improvements (about 95%) when changing from the power of one to the power of two.

Key words:- DEM/DTM/DSM, Ground Surveying, IDW, Digital Mapping, Spatial Accuracy

INTRODUCTION

DEMs are widely used in remote sensing and Geographical Information Systems (GIS) as they are mainly used for ortho-rectification of images, topographic mapping and engineering design and modeling. Furthermore, DEMs are used in numerous disciplines, ranging from geo-information to Civil Engineering. In various applications DEM serves as inputs for decision making, as examples they are employed in flood hazards analysis [1], [2]. Prior to the use of DEMs in various applications it is important to identify their qualities in order to determine the suitability of a certain DEM to the quality standards necessary for a specific application [3], [4], [5]. The quality of a

DEM is subjected to some factors such as the density of the sampling points, the spatial distribution of the sampling points, the method of interpolation used, the propagated errors from the source data in addition to other factors [6], [7].

Elevation interpolation is a complicated operation that can be defined as a process of predicting a value of attribute z at unsampled site from measurements carried out at neighbouring sites within given neighborhoods. The process aims at creation of discrete continuous surface from observations at sparsely located points or for resampled grid to different density or orientation as in remote sensing images [1]. Elevation interpolation could be considered as a spatial filtering process where the input data are not necessarily located at on a continuous grid. Interpolation operations can be expressed in a mathematical command language, however most users will encounter specialist packages so that standard terminology can be used. It may be useful to mention that predicting an elevation value outside the site area from the point data is known as extrapolation [8]. The main purpose of an interpolation operation is the conversion of point data files into continuous fields so that the spatial patterns of these measurements can be compared with the spatial patterns of other entities [9]. Interpolation operation is applied when the discretised surface has different levels of resolution from the required surface. It may also be applied when the continuous surface is represented by different models. Moreover, interpolation operation is performed when the data available does not cover the domain of the area of interest [10].

Interpolation methods may be divided into two main groups, global interpolation and local interpolation techniques. Global interpolation uses all available data to provide prediction of the whole area of interest. On the other hand, local interpolators operate within a small zone around the point being interpolated to ensure that the estimates are made only with data from locations in the immediate neighbourhood and fitting as good as possible. As examples of global interpolation methods, classification using external information, trend surface on geometric coordinates, regression models on surrogate attributes and the methods of spectral analysis. On the other hand, local interpolation techniques encompass thiessen polygons and pycnophyactic methods, linear and inverse distance weighting and thin plate splines. Global interpolations in most cases are not used for direct interpolation but for examining the effect of global variations and sometimes removal of this effect that may be caused by major trends. As soon as the effect of global variations in the data is removed the data can be interpolated using local interpolators. All global and local interpolation methods are relatively straightforward as they require only understanding of simple statistical methods. Commercial GIS packages usually include these methods. Geo-statistical interpolation using methods of spatial autocorrelation is known as kriging as they require understanding of the principles of statistical spatial autocorrelation. These methods are used when the variation in elevations is so irregular and the density of the sample is such where simple interpolation methods may not give reliable predictions [8]. Asal and Hassouna, (2007) studied the effect of the interpolation techniques on the quality of the obtained DEM [11]. The outcome of the research indicated that IDW provides better quality DEM than that is given by the spline method which smoothes the surface and generates quite noise DEM. The research did not answer the question which value of the power is to be used with the IDW for providing a DEM of a specific quality

The Inverse distance Weighting (IDW) methods of interpolation combines the ideas of proximity adopted by thiessen polygons with the gradual change of the trend surface. It is assumed that the value of an attribute z at unvisited point is a distance weighting average of data points occurring within a neighbourhood or window surrounding the unsampled point. The original data points may be located on a regular grid as well as they can be distributed irregularly over an area where interpolation is performed to locations on a denser regular grid in order to produce a map. The weighted moving approach computes the interpolated elevation as [8], [10]:

$$z = \sum_{i=1}^{n} \lambda_i z(x_i) \quad \text{and} \quad \sum_{i=1}^{n} \lambda_i = 1 \qquad (1)$$

where:

λ_i = the weights which are functions of the position of the point i, Thus,
$\lambda_i = \varphi\,(d(x, x_i))$

The value of φ(d) tends to the measured value as d tends to zero which is given by the exponential function e^{-d} and e^{-d^2}. The most common form of φ(d) is the inverse distance weighting predictor whose form is [8]:

$$z(x_j) = \sum_{i=1}^{n} z(x_i) d_{ij}^{-r} \Big/ \sum_{i=1}^{n} d_{ij}^{-r} \qquad (2)$$

where,

x_j = the points where the surface is to be interpolated,
x_i = the data points.
r = the power of the formula which can be 1, 2, …., n

As in equation (2) φ(d) tends to infinity as d tends to zero, the value of the interpolated point that coincides with a data point must be copied over. The simplest form of this interpolation is called linear interpolator, in which the weights are computed from a linear function of distances between sets of data points and the points to be predicted. It should be noted that the inverse distance weighting is forced to the exact values at the data points. This means that if the input grid coordinates are equal to those of a sampling point, then the interpolated elevation at this location will be copied over by exact elevation value of the sampling point. The quality of the DEM produced from the IDW interpolation may be assessed by using additional observations as the method has no inbuilt technique for testing the quality of interpolation [8], [10].

MATERIA L AND METHODS

Test site and Methodology

A test site in a hilly corrugated terrain has been established to the east of Cairo, Egypt. Data has been collected from field using conventional surveying methods where a total station instrument has been used for measuring the three dimensional coordinates (x, y, z) of spot points. DEMs have been created from the field data using ESRI spatial analysis and 3D analyst working under ArcView GIS 3.2 commercial software package. All parameters have been kept unchanged except the power of the IDW which is the only parameter allowed to change for the creation of DEMs using powers ranging from one to ten. Three testing methods have been exploited for the assessment of the variation in the generated DEM due to the change of the power of the IDW; the analysis of the countourline maps generated from the difference between DEMs, testing cross and longitudinal profiles generated from the DEMs and finally assessment of the DEM accuracy using independent external checkout points that considered as ground truce measurements in the analysis.

Digital Elevation Measurements

Figure 1 shows digital elevation measurements which have been collected from field covering an area of about 830 by 660 metres and consisting of 2687 spot elevation measurements forming a density of an elevation point for every 203.87 squared metres and an average spacing between spot elevations of about 14.28 metres. The maximum elevation in the sample data is 138.27 metres while the minimum elevation is 116.73 metres above the mean sea level giving a range of elevations of 21.84 metres in the test area. The mean elevation of the sample data is 128.76 metres and the median is 129.62 metres while the mode of the sample data records two values of equal frequencies; 131.96 and 131.07 metres. Additionally, the variance of the sample is 18.68 squared metres and the standard deviation of the mean is ±4.32 metres which is quite high value referring to highly varied terrain.

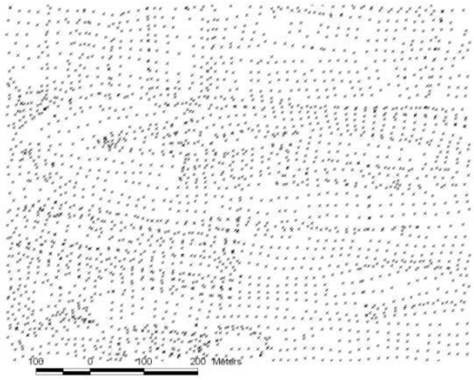

Figure 1: Digital elevation measurements

RESULTS AND DISCUSSION

Contour-Lines of the Difference Between DEMs

The idea behind this test depends on considering the DEM created from IDW with power value of ten is a reference DEM where the spatial differences between this DEM and the DEMs created using powers from one to nine are computed and analyzed. Contourline maps have been created from the DEMs of the differences and draped over the DEM created from the power of ten. Figures from figure 2 to figure 10 show the contourline maps of the differences between the DEM generated from IDW of power ten and each of the DEMs created using varying powers starting from power one to power nine respectively. Also, Table 1 summarizes the statistical properties of the contourline maps created from the nine DEMs of the differences that have been generated before.

Referring to figures from figure 2 to figure 10 it can be seen that contourlines are very crowded and very dense in figures from figure 2 to figure 5 especially in hilly corrugated parts of the DEM. Starting from figure 6 the density of the contourlines becomes less and decreases with the increase of the power of the IDW. Also, the density of the contourlines is higher at the transition locations between colour classes in hilly corrugated landscapes compared to that in mild gentle terrains which is an indication of interpolation difficulty in hilly corrugated landscapes. This is also, noticeable from the contour values in hilly corrugated terrains where they are quite high while contours are of smaller values in gentle terrain regions.

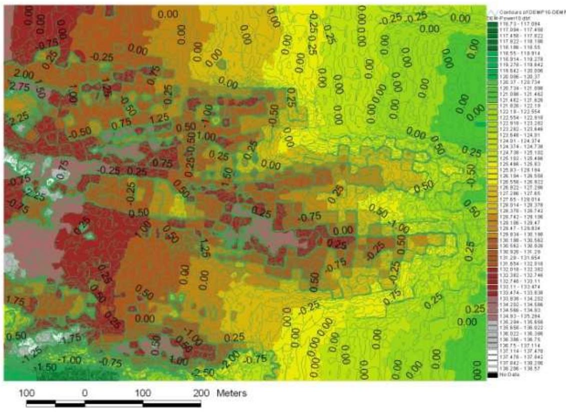

Figure 2: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of one.

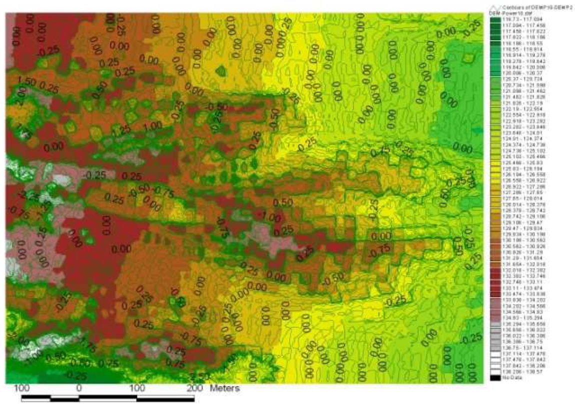

Figure 3: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of two.

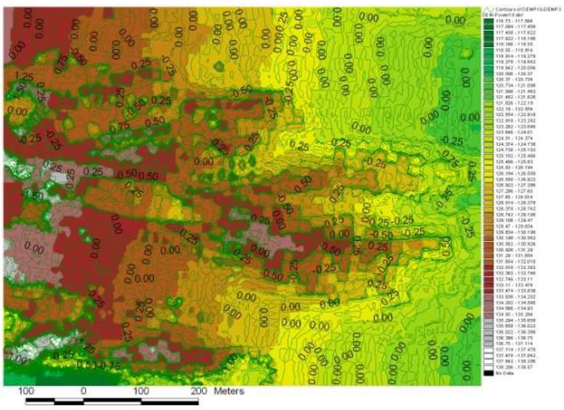

Figure 4: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of three.

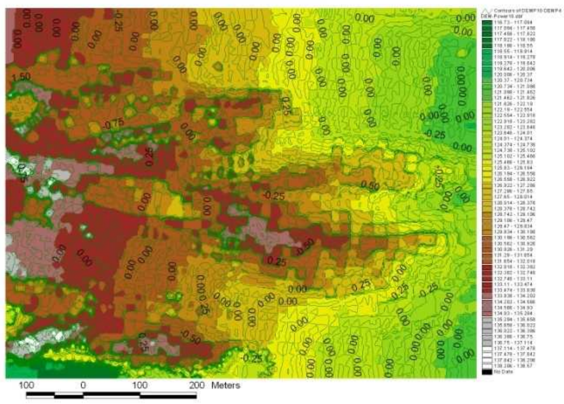

Figure 5: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of four.

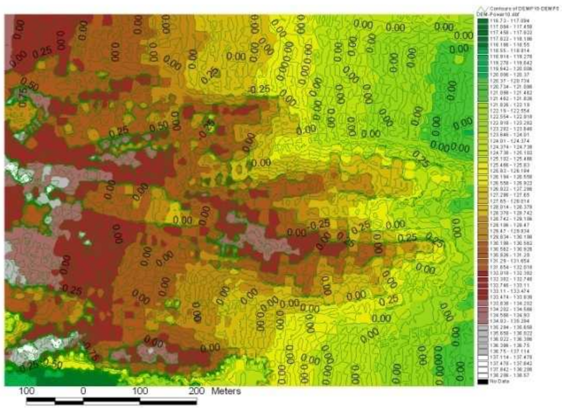

Figure 6: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of five.

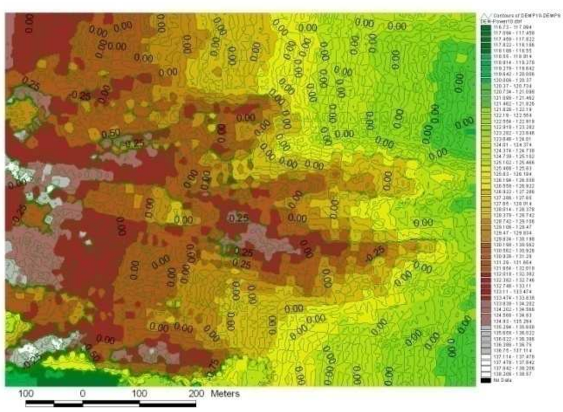

Figure 7: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of six.

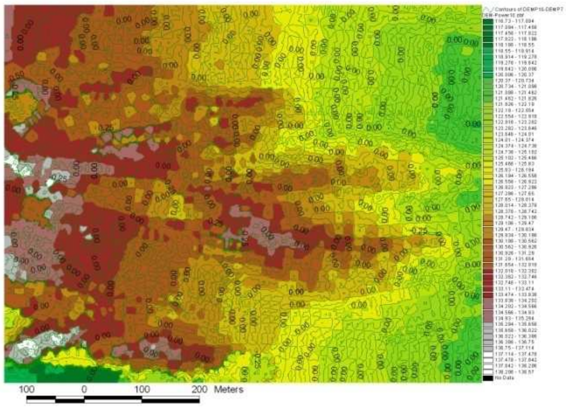

Figure 8: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of seven.

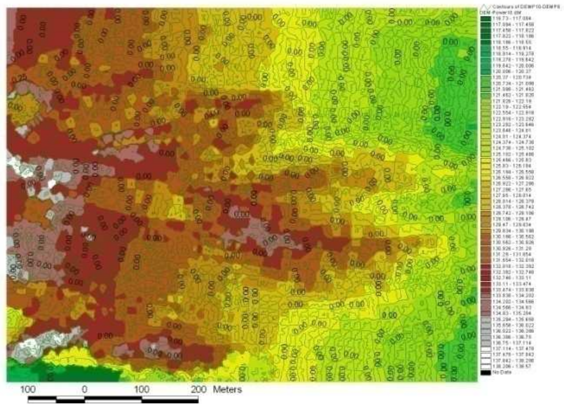

Figure 9: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of eight.

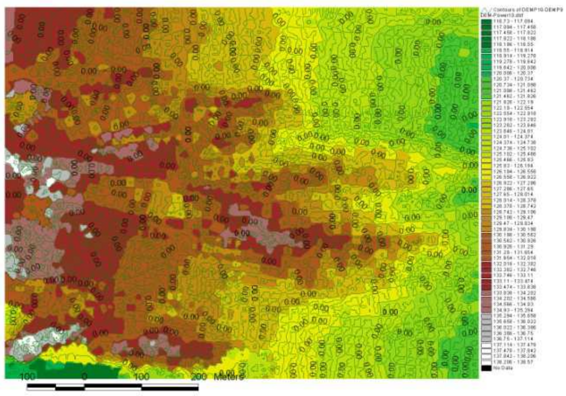

Figure 10: Contourlines generated from the differences between the DEM of power of ten and the DEM of power of nine.

The outcome from the visual analysis of the contour maps is supported by the results in table 1 where it is noticeable that the maximum value of the contourlines decreases with the increase in the power of the IDW where the maximum contour of the difference is recording 7.25 meters with power one and 0.500 metres with power nine. The same is said for the minimum contourline; where this is -10.75 metres with power one and -0.75 metres with the use of power nine. This convergence between the maximum and minimum differences is reflected upon the range of the differences which decreases with the increase in the power of the IDW. The absolute value of mean of the difference is decreasing with the increase in the power of the IDW approaching to zero with the use of power nine. Additionally, the median is always at zero while the mode is recording zero with the use of high powers. The same can be said with the standard deviation of the contours of the difference where it is 1.507 meters with the case of power one and decreases to be 0.06 metres with the use of power of nine.

Table 1: Statistical analysis of the contourline map of the difference between the DEM of power ten and the DEMs of varying powers starting from power one till power nine.

Statistical Value	Contourline Map of (DEM P10 – DEM P1)	Contourline Map of (DEM P10 – DEM P2)	Contourline Map of (DEM P10 – DEM P3)	Contourline Map of (DEM P10 – DEM P4)	Contourline Map of (DEM P10 – DEM P5)	Contourline Map of (DEM P10 – DEM P6)	Contourline Map of (DEM P10 – DEM P7)	Contourline Map of (DEM P10 – DEM P8)	Contourline Map of (DEM P10 – DEM P9)
Sum	-1069.00	-862.75	-604.00	-401.75	-249.250	-140.250	-57.750	-25.250	-4.250
Count	5941	5706	5433	4850	4126	3315	2349	1591	1238
Max.	7.25	6.5	5.500	4.500	3.500	2.500	1.7500	1.00	0.500
Min.	-10.75	-9.25	-7.500	-6.000	-4.750	-3.500	-2.500	-1.500	-0.750
Mean	-0.18	-0.1512	-0.111	-0.0828	-0.060	-0.042	-0.025	-0.016	-0.003
Median	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mode	-0.25	-0.25	-0.25	0.25	0.25	0.00	0.00	0.00	0.00
Range	18	15.75	13.00	10.500	8.250	6.00	4.25	2.5	1.25
Variance	2.27	1.571	0.997	0.606	0.35	0.189	0.092	0.031	0.0036
Standard Deviation	1.507	1.253	0.998	0.778	-0.083	0.435	0.303	0.176	0.06

Analysis of the Profiles Extracted from the DEM

Profile testing is a technique used for exploring differences between DEMs created from different powers. Figure 11 is a longitudinal profile A-B while figure 12 is a transverse profile C-D; each of them has been created from ten DEMs created using IDW with different powers starting from power of one and ending by power of ten. From both figures it is clear that the profiles from the DEM created using IDW with power one is recording differences from the DEMs created with the use of powers of higher values. Differences in elevations are at their highest value at hilly and depressed parts of the profile. At some parts of the profiles differences in elevation may exceed 1.5 metres. From the profiles also, it is noticeable that IDW with power one gives a DEM with high degree of smoothing and approximating of elevations. The situation becomes better with the use of power two where the profiles are more corrugated and showing less degree of smoothing in the DEM. More improvements are obtained in the profiles from the DEM generated using powers of three and four but still there are some differences from the profile created with higher power values. The profiles obtained from the DEMs created from IDW of powers five, six, seven, eight, nine and ten run very close to each other and at some parts of the profile they coincide with each others. However, at sharp edges of the terrain differences between those profiles may be much clearer.

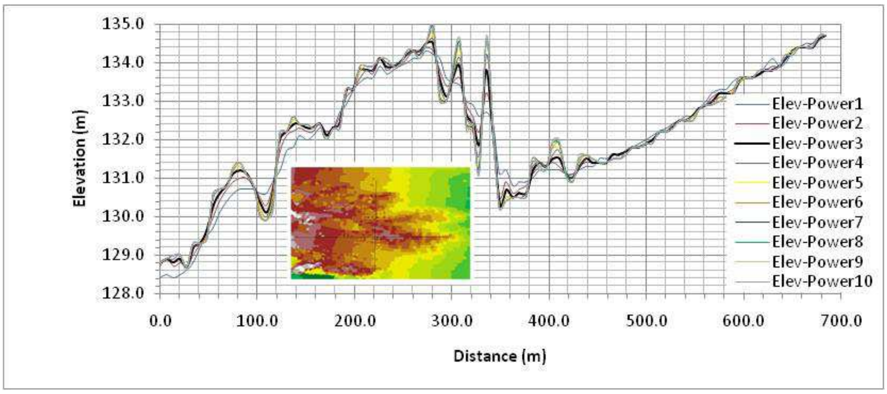

Figure 11: Profile A-B in the DEMs created from spot elevation measurements using IDW of varying powers starting from power of one to the power of ten.

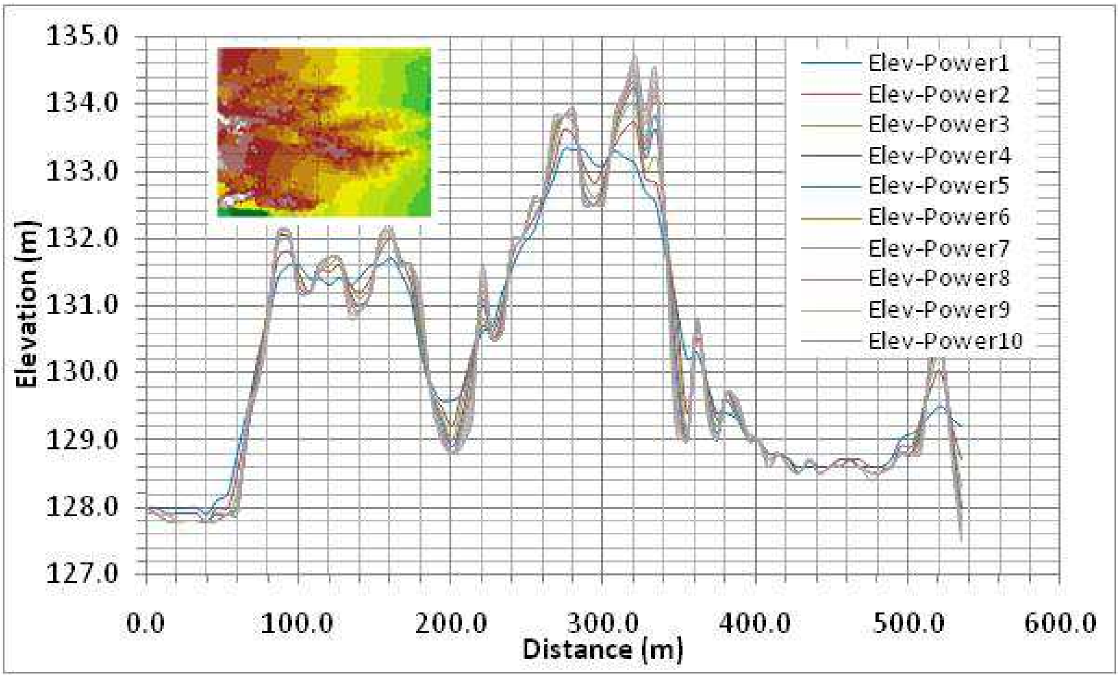

Figure 12: Profile C-D in the DEMs created from spot elevation measurements using IDW of varying powers starting from power of one to the power of ten.

Analysis of the Accuracy of the Elevations Extracted from the DEMs

This analysis depends on the use of a handful of checkout points distributed as uniformly as possible allover the DEM. The elevations of the checkout points have been determined from field using the same observing techniques used in measuring the spot elevation data. The checkout point measurements are considered as ground truths in the analysis of the accuracy of elevations extracted at the same locations from the interpolated DEMs using IDW of varying powers. Figure 13 depicts the locations and the codes of 72 spot elevation points that have been retained from the elevation data measurements and separated from the original data to be used as checkout points for the assessments of the accuracy of the DEMs. Interpolated elevations at the locations of the checkout points have been extracted from the ten DEMs. The residual vector representing differences between the elevations of the ground truth points and the interpolated elevations at the same locations has been assessed for every DEM. The statistical analysis of the computed residuals has been performed for the purpose of the assessment of the accuracy of each DEM created with a certain power. Table 2, depicts the results of the residual vector analysis at the checkout locations for the ten DEMs. From the table it is noticeable that the DEM generated using the power of one is recording the highest values of the sum of residual while the sum value decreases with the increase in the value of the power of the IDW. Also, the maximum value of the residual is decreasing with the increase in the power of the IDW. However, the minimum value of the residual is increasing with the increase in the power of the IDW making convergence with the maximum value which is reflected on the range of the residuals as it decreases with the increase in the power of the IDW. Additionally, the mean residual is decreasing with the increase in the IDW power. The same can be said for the median residual. The mode residual is recording zero with all IDW powers. Alternately, the variance and the standard deviation of the residuals are decreasing with the increase in the power of the IDW. The standard deviation represents the accuracy of the elevations extracted from the DEM due to the interpolation operation only while the errors in the spot elevation measurements are not considered in this research. The sum of elevation residuals and the standard deviation quantities are selected to be represented graphically against the value of the power of the IDW used in generating the DEM in figure 14 and figure 15 respectively.

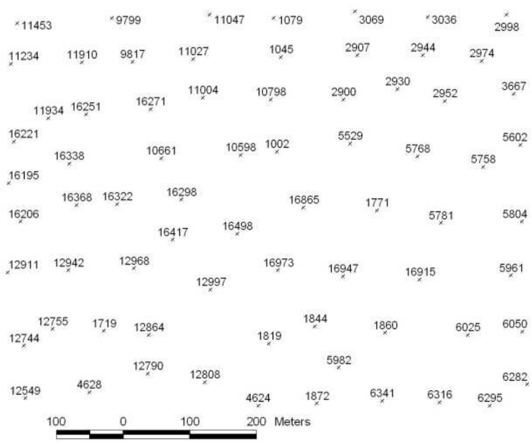

Figure 13: Distribution of the external checkout points over the test area.

Referring to Figure 14, there is sharp decrease in the sum of the residuals at the checkout point locations when using IDW of power two. The decrease in the sum of residuals continues with the increase in the power of the IDW but with a smaller rate. The same is derived from figure 15 which is a relationship between the standard deviation of the extracted elevations and the IDW power. From figure 15 there is improvement in the standard deviation of the derived elevations from the DEM with the increase in the power of the IDW, however, this improvement is big and reaches to about 95% of the total improvement when using the power of two. Very slight improvements are obtained with increasing in the power of the IDW more than two.

Table 2: Accuracy analysis of the digital elevation model generated from the IDW technique of varying powers using independent checkout points with measured elevations.

Statistical Value	DEM created using Power1	DEM created using Power2	DEM created using Power3	DEM created using Power4	DEM created using Power5	DEM created using Power6	DEM created using Power7	DEM created using Power8	DEM created using Power9	DEM created using Power10
Sum	34.602	16.240	14.051	15.352	14.631	13.860	13.420	12.001	11.984	11.267
Count	72.000	72.000	72.000	72.000	72.000	72.000	72.000	72.000	72.000	72.000
Max.	17.301	5.253	5.039	4.784	4.520	4.2720	4.058	3.888	3.772	3.782
Min.	-2.041	-1.969	-1.928	-1.870	-1.844	-1.8280	-1.537	-1.905	-1.832	-1.810
Mean	0.468	0.226	0.195	0.213	0.203	0.1925	0.186	0.130	0.166	0.156
Median	0.077	0.059	0.047	0.050	0.043	0.0275	0.025	0.013	0.016	0.021
Midrange	7.630	1.642	1.556	1.457	1.338	1.2220	1.261	0.992	0.970	0.986
Mode	0.000	0.000	0.000	0.000	0.000	0.0000	0.000	0.000	0.000	0.000
Range	19.342	7.222	6.967	6.654	6.364	6.1000	5.595	5.793	5.604	5.592
Variance	4.819	0.859	0.843	0.790	0.771	0.7662	0.757	0.755	0.751	0.751
Standard Deviation	2.195	0.927	0.918	0.889	0.878	0.875	0.870	0.869	0.867	0.867

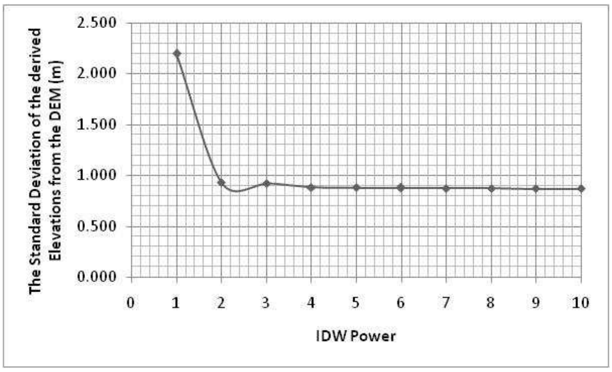

Figure 14: The sum of the residuals of the extracted elevations at the locations of the checkout points against the IDW power.

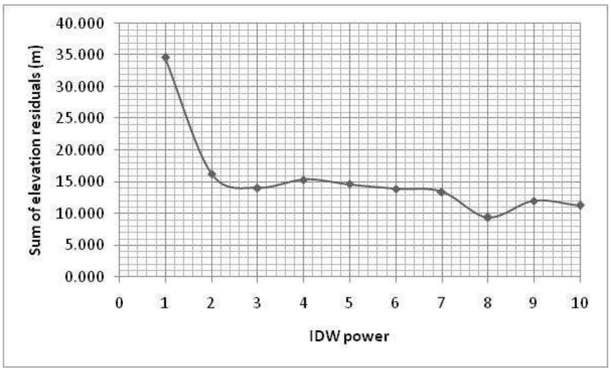

Figure 15: The standard deviation of the extracted elevations at the locations of the checkout points against the IDW power.

DISCUSSION

Three tests have been performed for assessing and quantifying the quality of the DEMs interpolated from spot elevation data using IDW interpolator with varying powers; The contour-lines of the difference between DEMs, the profile testing and the accuracy analysis of the Extracted elevations from the DEMs using checkout points. The first test has been basing on assuming that the DEM obtained from IDW of power of ten as a reference and subtracting the other DEMs generated with powers starting from one to nine from it and producing contourline maps from the resulting DEMs of the differences. Visual analysis has shown higher concentration of contourlines at highly corrugated landscapes compared to the concentration at gently mild terrains. This refers to difficulty in interpolating elevations in highly corrugated areas. This situation has improved with increasing the power of IDW; however the improvement is considerable till the use of power of four and becomes smaller for power values higher than four. The outcome of the visual analysis of the contourline maps is supported by the statistical analysis of these maps regarding the count of the contourline in the map, the maximum, the minimum contourline, median contourline, mode contourline, the variance and the standard deviation of the contourlines. The changes in the characteristics of the contourline maps interpreted by both visual and statistical analysis of the contourline map can be translated as improvements in the characteristics of the DEM due to increasing the IDW power.

The profile testing has shown some features that support the outcome from the contourline map of the difference test, where at breaklines of the terrain IDW with power of one is facing the maximum difficulty in estimating elevations and having a tendency of smoothing and approximating of the DEM. Also, the maximum differences between profiles from lower power DEMs and those from higher power DEMs have occurred at the corrugated areas of the terrain while at mild terrain the profiles from different DEM run close to each others. The degree of elevation smoothing in the profiles has been improving with increasing the power of the IDW but the improvement is very clear in the profile from DEM of power of two and that of the power of three. With DEM of power of four and more than that the rate of improvement is less where the profiles run very close to each others.

For the assessment of accuracy of the elevations derived from DEMs generated from IDW of different powers, the checkout point test has been used. The analysis of elevation residuals from different DEMs has gone on the same trend of the improvements in the DEM characteristics obtained from the other two tests. However, in this test most of the improvements in elevation accuracy have been achieved when using power of two where the standard deviation is recording about 95% of the total improvement. With the use of powers; three, four and so on improvements in accuracy of the derived elevations are still occurring but with very low amounts. The outcome from the analysis in this research benefits in drawing some concrete conclusions that can be in the interest of the Geomatics community who are everyday involving in producing DEMs from different technologies and employ them in various Engineering and Environmental aspects.

CONCLUSION

Digital elevation data can be obtained from conventional surveying techniques, photogrammetry and LiDAR technologies in discrete point file formats to be utilized in the creation of digital elevation models through the application of an interpolation approach. Different interpolation algorithms exploited in such operation are expected to provide DEMs of varying qualities. Inverse Distance Weighting (IDW) algorithm is one of the interpolation algorithms that are widely used in generating DEMs. IDW can be performed with different values of the power factor with the expectation of giving DEMs of different qualities. Spot elevation data collected from a corrugated hilly terrain test site has been used for the analysis. DEMs have been created from the test data with changing the value of the power of the algorithm starting from one to ten. Three tests have been performed on the generated DEMs; the countourline map of the difference test, the profile test and the checkout points test. The outcome of the tests can be summarized in the following points:

- There is high concentration of contourlines at highly corrugated landscapes compared to the concentration at gently mild terrain which refers to difficulty in interpolating elevations in highly corrugated areas.
- The interpolation operation improves with increasing the power of the IDW; however the improvement is considerable till the use of power of four and becomes smaller for powers values higher than four.

- At breaklines of the terrain IDW with power of one faces the maximum difficulty in estimating elevations with a tendency of smoothing and approximating the DEM.
- The maximum differences between profiles from lower power DEMs and those from higher power DEMs occur at corrugated parts of the terrain while at mild terrains the profiles from different DEMs run close to each others.
- The accuracy of the DEM records maximum percentage of improvements when changing from power of one to power of two (about 95% of the total improvements).
- For production of the optimum DEM other factors affecting the accuracy of the DEM such as the sampling unit size and the number of nieghbours could be useful for further investigations.

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