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COMPARISON OF DIGITAL ELEVATION MODELLING METHODS FOR URBAN ENVIRONMENT

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ABSTRACT

This paper discussed comparison of three Digital Elevation Modelling (DEM) Interpolation methods, namely TIN, IDW, and KRIGING. This paper tries to find which model can produce the best estimation for DEM construction when the same dataset is used for all of the methods. Two parameters are used to measure the accuracy of resulted DEM, which are the Mean Error and the Root Mean Square Error (RMSE). The results from the DEM generation show that TIN consistently produce a higher Mean Error and RMSE compared to other methods, which indicate that this method has a relatively low accuracy when used to construct a DEM. On the other hand, IDW and KRIGING have a similar accuracy for constructing DEM. Therefore, another method of assessment such as visual assessment is recommended to evaluate which method is the most suitable to construct a DEM.

Keywords: digital elevation modelling (DEM), TIN, IDW, KRIGING.

1. INTRODUCTION

Digital Elevation Modelling (DEM) is one aspect of computer systems implementation to simulate real world phenomenon. In the field of Geographic Information Sciences (GIS), DEM plays a role as one of the basic data requirement that has been widely used in GIS data structures. The definition of a DEM construction is the modelling technique of earth surface from existing data, such as height points, into a surface that shows an elevation values for the whole covered area. In short, a DEM is a representation of the surface of a terrain in a digital format. DEM can also defined as a geographic function that represents a terrain elevation data (Yue *et al*. 2007; Konan, 2011; Gens, 1999; Gooch and Chandler, 2001; MacMillan *et al*. 2004). The main purpose of the construction of a DEM is to represent surface elevation, which is an essential aspect in spatial analysis (Mark *et al.* 2004). The most widely used method to generate the DEM is by using point data that contain the value of latitude and longitude coordinates and the value of elevation for each point, measured from sea level.

There are different interpolations methods that can be implemented to construct DEM using height point data. When constructing a DEM, researchers usually only using one interpolation method, then the accuracy of the resulted DEM is evaluated, to decide if it is sufficient to be used as an input for further analysis. To help researchers decide which method is the most suitable, this paper tries to compare one method to another to give general overview about different DEM interpolation methods.

2. DEM INTERPOLATION METHODS

A typical procedure for constructing a DEM is collecting point data that contain elevation values, and then interpolate it with a particular method to transform those points into a surface that shows the elevation values that covers the area of interest. Each of the interpolation method has its own advantages and drawbacks. Thus, before implementing a particular method to generate DEM, it is important to evaluate which method is the most suitable for the study area. The most commonly used interpolation methods that are evaluated in this paper are the TIN, the IDW, and the Kriging interpolation methods. To evaluate which method can produce the most suitable DEM to represent urban environment, DEM quality assessment is discussed for each of the method and their comparison one to another.

2.1 TIN

The Triangulated Irregular Network (TIN) is an interpolation technique that calculates the elevations of the surface by digitally create ridgelines from height point data (Jordan, 2007). The elevation values along those constructed ridgelines are calculated from the initial elevation surface, and then, the DEM is constructed by using those elevations of ridgelines. The main difference between TIN and other DEM interpolation methods is that TIN in principle is a data model in the vector form, which represents features as polygons, points, and lines, together combined to represent surface elevation. In TIN, the input data is maintained while generating the surface model, because construction of DEM using TIN does not requires transformation from vector to raster data format. Therefore, the TIN surface is dynamic elevation data, because height points can be placed in an irregular manner on the whole area of interest. The main advantage of this approach is that TIN surface may have a higher resolution in such areas where the elevation values are highly fluctuating, or where a higher detail is required. (Zulkarnain, 2006), as shown in Figure-1.

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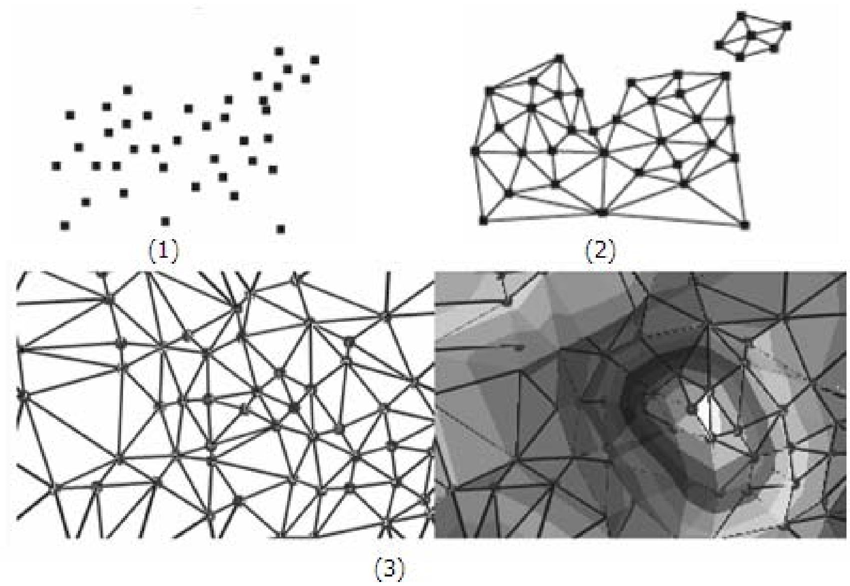

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(1) Nodes, the fundamental building blocks of a TIN.
(2) Every node is joined with its nearest neighbours by edges.
(3) DEM constructed from TIN

Figure-1. TIN interpolation method.

Another method of DEM construction is by using a TIN is by utilizing break-lines of the line features on the surface, which can be considered representing notable natural or man-made changes on the surface. Three types on break-lines can be used is when generating a TIN, which are hard break-lines, soft break-lines and fault lines. TIN generated by soft break-lines will make sure that existing elevation values along the lines are included in the TIN. Soft break-lines can also be utilized to keep the lines and polygons by implement them as the break-lines of TIN. Furthermore, no elevation changes are defined by the soft break-lines. On the other hand, hard break-lines define locations where sudden changes of elevation exist, such can be observed on rivers, cliffs, ridges, and buildings. Lastly, the fault break-lines are utilized to represent discontinuity on the surface, usually in the form of buildings and infrastructures.

2.2 IDW

The Inverse Distance Weight (IDW) is a common method to construct a DEM, which is based on the assumption of Spatial Correlation between distance and weight of elevation data. The main assumption of IDS is that the closer height points are one to another, the more likely they will have similar elevation values. The IDW is an exact interpolation method, where the maximum and minimum elevation value of the resulted DEM can only occur at the sample points. DEM created by IDW interpolation will become clustered, with outliers present. IDW presumes that the elevation values are influenced by the local variations, which can be evaluated using neighbourhood calculations. Therefore, in IDW, predicting the elevation data of any unmeasured location is by measuring values that surround it. This means that for each cell, an elevation data is calculated by nearby height points. The closer a height point closest to unmeasured location, the more influence the point have. There are two main parameters of IDW interpolation method, which are the power value (p) and the Root Mean Square Prediction Error (RMSPE) as shown in the Figure-2 below.

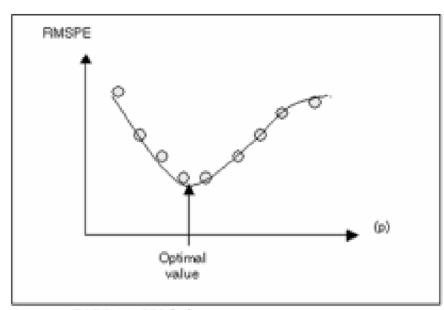

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Figure-2. IDW Parameters.

From Figure-2 can be concluded that the influence of a height point diminishes with the increase of distance between the height point and unmeasured location. The weights of each of the height points are strongly related to the distance of points, which is raised by the power value p. The result is, if the distance

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increases, the weights will rapidly decreases. Thus, the power value (*p*) determines the decrease rate of the weights. The optimal value (*p*) value then calculated by minimizing the inaccuracy of the resulted DEM, which is the Root Mean Square Prediction Error (RMSPE). This is the statistical parameter that is calculated by cross-validation between input and output data. Each measured point in cross-validation is removed, and then, compared to generated DEM.

2.3 KRIGING

The Kriging interpolation is a probabilistic method of DEM construction that predicts the elevation of a point on the surface by the aggregation of the elevation values of nearby height points. The main assumption of Kriging interpolation is that values at a shorter distance are more likely to be similar than values at a larger distance. Kriging compares elevation value for each of the height point pair, and then, a statistical variance or covariance is calculated. The spatial structure of the surface then predicted using a semi-variance method (Zulkarnain 2006). The spatial dependence of height point pairs can be calculated with the following equation:

$$\gamma(h) = \tfrac{1}{2}\sum_{i=1}^{m}\left[\left(Z\left(xi+h\right)-Z(x)\right)^2\right] \tag{1}$$

Where

γ (h) = The value of semi-variance

m = Pairs of Points within *h* distance

Z (*x*) = Elevation data at position *i*

Z (*xi* + *h*) = Elevation data at h distance from i

The height points are evaluated using the semi-variogram statistical test, and then used to assign a weight for each of the height points. The experimental semi-variogram graph is a plot that shows the semi-variance values of the elevation data on the *Y*-axis against the distance of elevation value on the *X*-axis. An appropriate mathematical function such as the Gaussian, the Exponential, or the Spherical function is needed after the calculation of the experimental variogram to model the spatial variation of the height points. The next step of the Kriging interpolation method is determining the values of the parameters that are required in the construction of DEM, which are the Nugget, the Sill, and the Range parameters. The Nugget parameter is the parameter of a semi-variance when the difference between elevation data approaching zero. The Sill parameter is a maximum semi-variance value's variability when the spatial dependence between height points is considered absence. The last one, the Range parameter, indicates the separation between pairs of height points where the sill is reached. The semi-variogram plot and its formula for Kriging interpolation are shown in the Figure-3.

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left\{Z(xi)-Z(xi+h)\right\}^2 \tag{2}$$

Where

n = Pairs of Points that are included within the distance *h*.

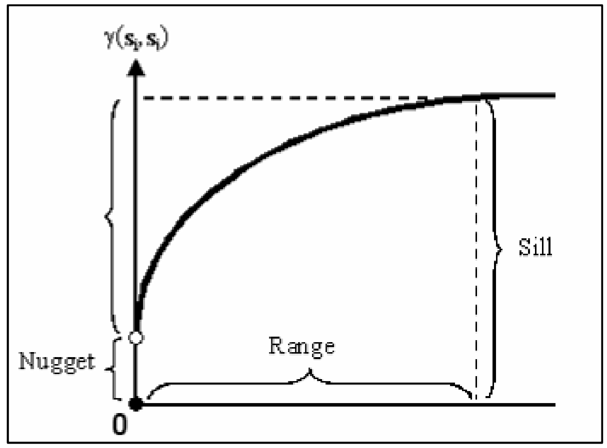

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Figure-3. Semi-Variogram plot.

The variance of the predicted elevation values is calculated based on both the predicted values and how the existing height point data are configured. The total sum of each of the height points must equal to one, which is assigned by fitting the variogram model (Pardo-Iguzquiza and Dowd 2005), with an additional criteria for optimization. These additional criteria serve a purpose to minimize the value of variance's prediction. The elevation values for unmeasured locations are calculated with the following equation;

$$Z_0 = \sum_{i=1}^{N}\lambda iZi \tag{3}$$

Where

Z_o = the predicted height value

λi = weights for participating height points

Zi = values of height points

2.4 DEM Quality assessment

To determine how accurate the constructed DEM can represent the real-world surface, its quality must be assessed. There are two methods than can be used for this purpose, which are either by a statistical analysis or by a visual assessment. The First method, which is the Statistical Analysis, in principle evaluates the predicted elevation value on every height point data by evaluating the similarity among predicted and measured values. The Root Mean Square Error (RMSE) is the most widely used

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method to evaluate the DEM's accuracy, which assumes that the errors are usually distributed with zero mean error. The validity of this technique is only acceptable if the measured errors are independent from the data collection's systematic error. On the other hand, the horizontal accuracy of RMSE only concerns with the two-dimensional positional accuracy (Zulkarnain 2006), using the following formula:

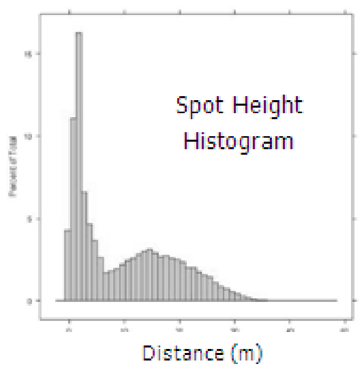
$$RMSE = \sqrt{\frac{\sum(Z_i - Z_j)^2}{n}} \quad (4)$$

Where Z_i is the predicted elevation value, Z_j is the measured value from field observation, and n is the number of height points.

The next method to assess the quality of DEM is by using a perception of a human observer to compare the constructed DEM with the actual elevation of the real-world surface with his visual assessment. The basic principle of this method is comparing the constructed DEM with the surface topology by using an observer's visual perception.

3. DEM CONSTRUCTION

In this paper, various DEMs are generated for Surabaya City, Indonesia, using existing height points. To make an accurate analysis, only height points between 0 to 10 meters above sea level are included in the construction of DEM. Three interpolation methods are used to convert height points that contain elevation data from field observations. Those three interpolation methods are TIN, IDW, and Kriging interpolation methods. After that, DEM quality assessment using the Root Mean Square (RMSE) value is evaluated to determine which DEM is the most suitable to represent the topology of urban environment. DEM generation in this paper were conducted using ArcGIS software, which requires 3D analyst and Geo-Statistics extensions. The height points to construct the DEM generation are the Spot Height data, which is owned by the Government of Surabaya City. Elevation data in this paper use cm as the elevation value. The detailed descriptions of the height points of this paper can be seen in Figure-4.



Number Of Points	56911
Minimum Value (m)	0.00
Median Value (m)	6.52
Mean Value (m)	9.61
Maximum Value (m)	46.02
Standard Deviation	7.60

Figure-Error! No text of specified style in document.**.** Overview of Height Point Data.

The First interpolation method to be evaluated is the TIN interpolation, in which height points are triangulated to construct a DEM. The height points converted to a surface by connecting a series of lines to construct a network of triangles, and then, using the Delaunay triangle criterion, a DEM is constructed. The main advantage of TIN interpolation is it doesn't require any parameters, because the DEM is constructed by using triangulation approach. On the other hand, the main drawback of TIN interpolation is that the Root Mean Square Error (RMSE) value cannot be calculated automatically using ArcGIS software, because TIN uses an exact elevation value for each intersection of lines. Therefore, height point data when TIN is implemented must be split into two sets, which are the data points that used to construct the model, and the data points that used to validate the model. And then, the Mean Error value and RMSE value are calculated to determine the accuracy of generated DEM.

Comparison between the values of dataset for validation and dataset for calibration produced two DEM accuracy indicators, which are the Mean Error and the Root Mean Square Error (RMSE). Using the height points for the study area, TIN interpolation resulted in the value of Mean Error Value of 0.015051. On the other hand, the value of Root Mean Square Error is 0.844.

The Second method of interpolation is the Inverse Distance Weight (IDW), which calculates the value of unobserved locations by their distance to measured locations. The main parameter for IDW is the Power Value (p). By using an extension of ArcGIS software, which is the Geo-statistics extension, the resulted p value is 3.4518. After the DEM is constructed, its accuracy is evaluated by the error prediction as follows;

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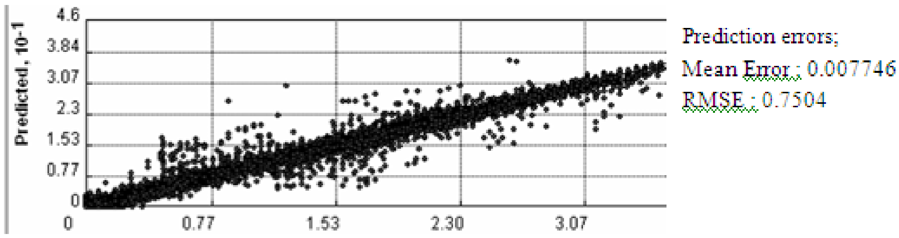

Figure-5. Cross-validation Plot of IDW.

The next interpolation method in this paper to create DEM from height point data is by Kriging interpolation based on a statistical model that includes auto-correlation between predicted and measured locations. Thus, not only the Kriging method has the capability to produce a predicted elevation of a surface, it also provides some measurements about the accuracy of the predictions. The main parameter of the Kriging interpolation method is a semi-variogram that describes the spatial correlation between measured height points. In this paper, the original variogram for the height point was evaluated using *R* software. The interpolation itself was calculated using ArcGIS. The parameters of the Kriging, which are the Nugget, Sill, and Range, were calculated in using Geo-Statistic extension within ArcGIS software, while the DEM is constructed using ArcGIS's Spatial Analyst's extension. Performing a Kriging requires constructions of variogram models to determine the values of the Nugget, the Sill, and the Range. Despite the original Semi-variogram already have these values, the fitted values of the Nugget, the Sill and the Range will be used as the parameters in the interpolation. In this paper, the Ordinary Kriging was implemented, using three variogram models; which are the Gaussian, the Spherical, and the Circular variogram models.

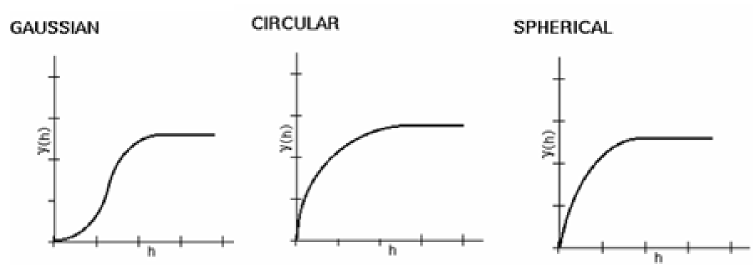

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Figure-6. Models of Semi-Variogram.

A. Gaussian

The first Kriging interpolation to construct a DEM for the study area used a Gaussian variogram model that assumes the semi-variogram has a low value in relatively short distance, and then after a certain point, the value of semi-variogram increases rapidly until reaches the Sill, as shown in the following figure;

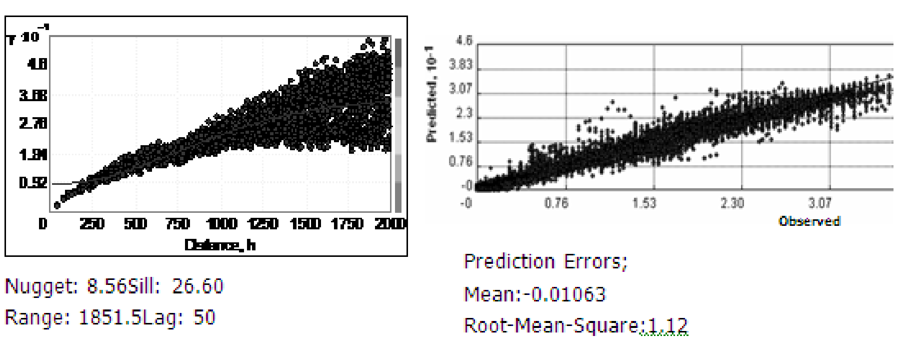

Figure-7. Gaussian Variogram Result and the cross-validations.

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Figure-7 above shows that using the Gaussian semi-variogram resulted in a relatively high RMSE, which indicates that this method is less accurate than IDW. The value of the standardized RMSE using this method is 1.12, while the IDW the value of RSME is only 0.75. This means that the Kriging interpolation using Gaussian variogram model is a not suitable to construct a DEM for an urban environment.

B. Spherical

The second Kriging interpolation to construct a DEM is uses a spherical-variogram model that describes rapid increase of semi-variance in short distance, and as the distance increases, the value of semi-variance is slowly reduced until it reaches the Sill. The result of Spherical-variogram model can be seen in the following figure;

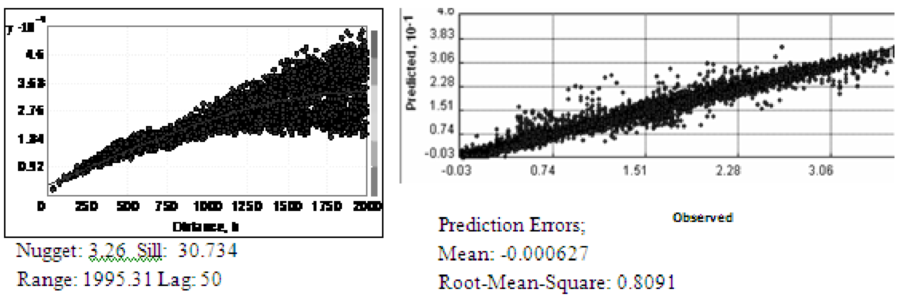

Figure-8. Spherical Variogram model and cross validations.

A Kriging interpolation method where the Spherical-variogram is implemented shows a better result than Gaussian-variogram. The value of the RMSE with this method is 0.80, which is much lower than Gaussian's RMSE. However, compared to IDW's RMSE, the Spherical-variogram still produces a little bit higher RMSE value, which indicates that this approach is also less accurate compared to IDW.

C. Circular

The final model of variogram that included in the Kriging Interpolation method is the Circular-variogram Model, which assumes that the value of covariance between the Nuggets and the Sill is a circular one. Thus, this variogram argues that there is a geometric form of the elevation values. The resulted DEM have a more regular shape compared to other semi-variogram models. The Figure-9 below shows that by using a Circular-variogram model for Kriging resulted in RMSE with the value of 0.856. Although this value is lower than Gaussian semi-variogram, it still has a higher value compared to the Spherical-variogram model. Thus, compared to IDW, this method resulted in a higher RMSE. Therefore the Circular-variogram model is not suitable to generate DEM for urban environment. The comparison of the interpolation methods that evaluated in this paper can be seen in Figure-10;

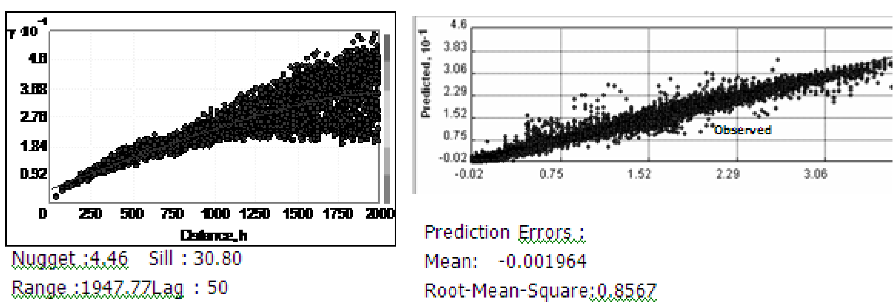

Figure-9. Kriging with The circular-variogram and the cross-validations.

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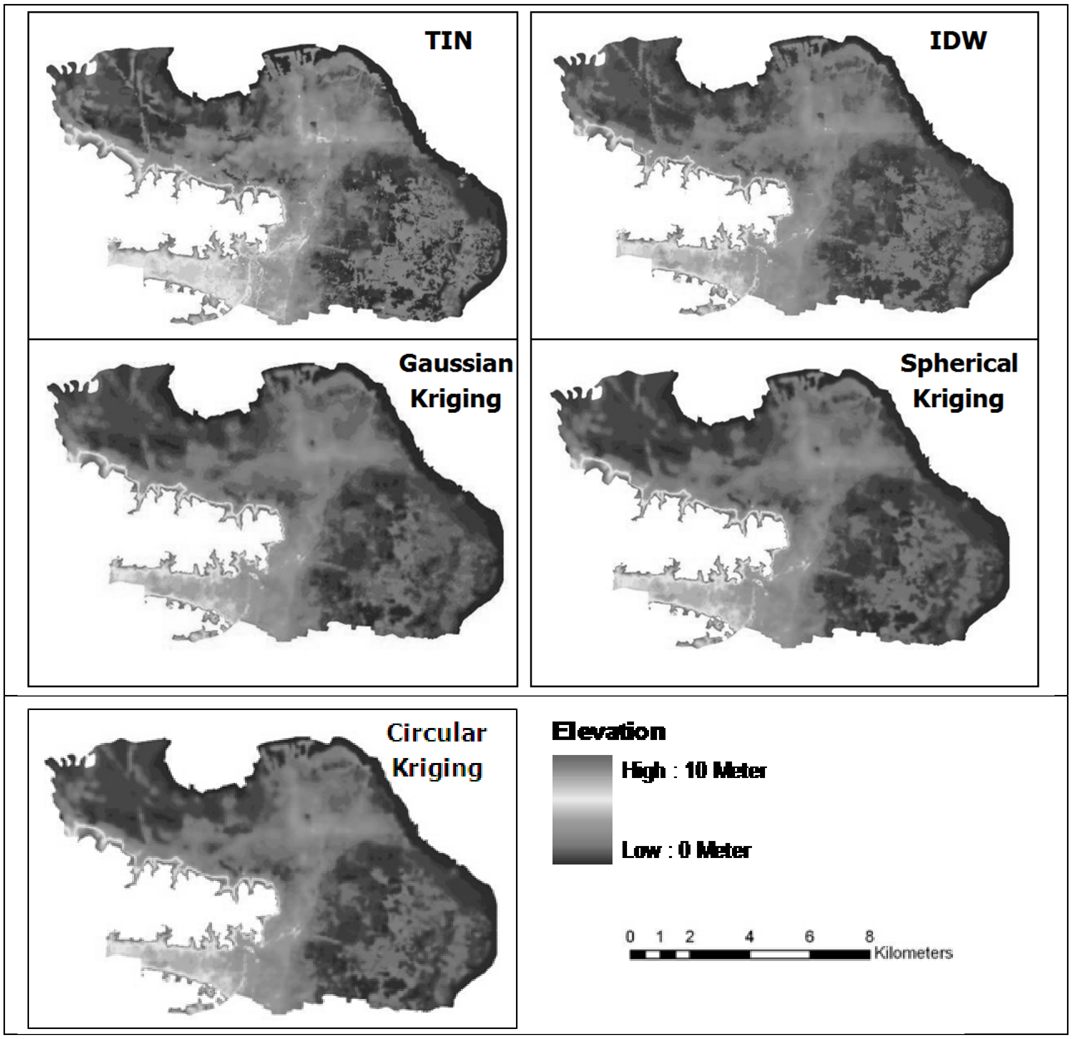

Figure-10. DEM construction with various interpolation methods.

DEM ACCURACY ASSESSMENT

The construction of DEM is one of the methods to represent the real-world surface in a digital form. DEM was widely used as an input for various spatial analysis, such as flood modelling, land suitability, and hazard mapping (Moore, Bell *et al*. 2005). Implementations of various interpolation methods on the same height point data as discussed above show that different interpolation methods will resulted in a different DEM accuracy. To decide which of the interpolation methods that can produce the best accuracy, the most widely used method is the Root Mean Square Error (RMSE). A relatively high value of RMSE indicates that the constructed DEM has a relatively low accuracy. DEM accuracy assessment can also be performed by calculating the value of the Mean Error, which indicates the global differences among predicted value and observation data. Values of the accuracy of DEM using different interpolation methods are shown in Table-1.

Table-1. DEM Accuracy for different interpolation methods.

Interpolation method	Mean error	RMSE
TIN	-0.015051	0.844
IDW	0.007746	0.7504
Gaussian Kriging	-0.01063	1.12
Spherical Kriging	-0.000627	0.8091
Circular Kriging	-0.001964	0.8567

Table-1 above shows that IDW method and Spherical Kriging resulted in the relatively similar accuracy of the constructed DEM. The RMSE of IDW is smaller, but on the other hand, the Mean Error of the Spherical interpolation is smaller. This results indicate an exact decision cannot be made if relying on statistical methods. Therefore, the Visual Assessment method is

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implemented to decide which interpolation method that can produce a DEM that suitable to construct a digital representation of topology on an urban environment. The visual assessment approach is based on the general knowledge about study area and common assumptions about topology of an urban environment.

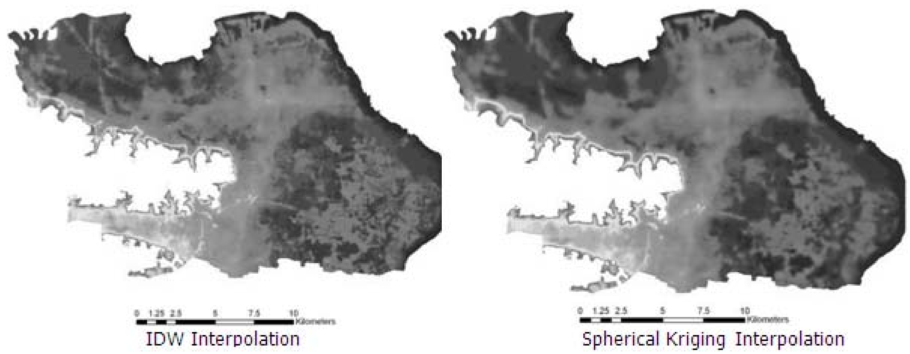

Figure-11. A Visual assessment for the generated DEM.

Figure-11 above shows that the DEM constructed by the IDW interpolation method has a crisper digital elevation representation. On the other hand, implementation of Kriging resulted in a fuzzier DEM surface. To represent the topology of an urban environment, crisper elevation is better because the values of elevation in urban environment often show abrupt changes. Therefore, the IDW interpolation method can be considered more suitable to construct a DEM in the study area.

CONCLUSIONS

DEM constructions using various interpolation methods resulted in a different degree of accuracy for each method. The DEM that was constructed by the IDW interpolation method shows a crisper surface, while the DEM that was constructed by the Kriging interpolation method shows a fuzzier surface. A crisper elevation can be considered more suitable to represent the surface of a built-up environment, because the value of elevation in urban environment often have a high difference of elevation in adjacent areas, due to the existing buildings and terrain modifications. Therefore, the IDW interpolation method is considered the most suitable method to construct a DEM in urban environment. On the other hand, when DEM construction requires a coarser result, such as landuse change and water catchment analysis, Kriging will be more suitable to be implemented to construct a DEM.

Latest satellite-based technology such as LIDAR may improve the accuracy of DEM construction if it combined with the spot-height approach that discussed in this paper. However, implementation of LIDAR and Interpolation methods usually conducted separately, where scholars prefers one method compared to the other. Therefore, future researches in DEM construction needs to explore the possibilities to combine Interpolation Methods and satellite-based approaches to improve the accuracy of generated DEM.

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