

# DIGITAL TERRAIN MODELING IN A GIS ENVIRONMENT

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## ABSTRACT

Digital terrain models (DTMs) in recent times have become an integral part of National Spatial Data Infrastructure (NSDI) of many countries world-wide due to their invaluable importance. DTMs play a major role in hydrologic modeling, sediment transport, soil erosion estimation, drainage basin morphology, vegetation, and ecology. DTM generation however has a setback of high cost of primary data input acquisition (i.e. elevation) and complexities in processing. Most DTM data are derived from photogrammetric data, satellite image data, laser scanning data, cartographic data sources, and ground surveys though accurate is expensive, time-consuming and require skilled personnel. This paper describes a low cost means to generate DTMs where elevation data is not readily available in digital form and when the accuracy of the output is not a dominant factor. The existence of large volumes of hardcopy topographic maps provides a source of primary input in the form of contours which can be digitised and used for DTM generation purposes. This research therefore aims at generating DTMs within a GIS environment using elevations digitized from topographical maps. That is, a geographic information system (GIS) based approach is presented for the development of a terrain model. After digitizing contours and points along contours from a topographic map, various interpolation algorithms were used to generate DTMs and their accuracies in terms of root mean square errors were assessed. The resulting surface model provides a good representation of the general landscape and contains additional detail information (such as slope, aspect, cross-sections, volumes, hillslope) to describe, evaluate and quantify terrain properties. Also, if the digital contours are geo-referenced, they can be readily integrated into existing GIS for 3D surface visualization and spatial analysis. Results of surface analysis (intervisibility analysis) are presented and among other applications, the DTMs proved useful in surface analysis.

## 1. INTRODUCTION

DTM is the digital representation of a portion of the earth's surface (Weibel and Heller, 1990). It has also been defined as a representation of land surface point elevations which is often used to represent relief. DTMs have been used to represent the terrain surfaces for road engineering, construction purposes, hydrologic modelling, sediment transport, soil erosion estimation, drainage basin morphology, vegetation, and ecology. Today, the advancement in both information technology and computing power and graphics visualizations capabilities have led to the rapid growth of DTM usage in many fields, such as route engineering, landscaping, land surveying and mapping, military-purpose mapping, remote sensing, geographical information systems (GIS). It has also in recent times become an integral part of national spatial data infrastructure (NSDI) of many countries world-wide due to their invaluable importance.

DTM generation in principles requires elevation data for the area you wish to investigate and a set of methods to derive terrain specific information.(Giger, 2000). Typically, sources of DTM data are derived from photogrammetric data, satellite image data, laser scanning data, cartographic data sources, and ground surveys though accurate is expensive, time-consuming and require skilled personnel. DTM generation however has a setback of high cost of primary data input acquisition (i.e. elevation) and complexities in processing.

It is therefore imperative that a quick, accurate and cost effective means of generating DTMs is devised to provide this

important 3D maps. This paper therefore describes a low cost means to generate DTMs where elevation data is not readily available in digital form and when the accuracy of the output is not a dominant factor. That is, the purpose of this paper is to generate DTMs using data extracted from contours. The existence of large volumes of hardcopy topographic maps provides a source of primary input in the form of contours which can be digitised and used for DTM generation purposes. In other words, the generation of DTMs from contours is emphasised because this is the major source of DTMs (Robinson, 1994; Dakowicz and Gold, 2003; Gold and Dakowicz, 2003; Vozenilek, 2004). Contourline maps contain a lot of topographic information, but part of it is contained implicitly and therefore is not easily accessible. For example, a hill will be flattened during the process of DTM generation (flat triangle problem often occurs when triangulating contour data), unless a elevation data has explicitly been measured (Dakowicz and Gold, 2003). Similarly, a ridge or a drainage line may disappear without a formline, indicating this topographic feature. As outlined in Dakowicz and Gold (2003), to preserve these features, a elevation for the hill and a formline for the ridge should be calculated. In addition, by explicitly defining points, their coordinates can be scaled more precisely than by estimating their positions in relation to nearby objects.

This research therefore aims at generating DTMs within a GIS environment using elevation data digitized from topographical maps. After digitizing contours and points along contours from a topographic map, various interpolation algorithms were used to generate DTMs and their accuracies in terms of root mean square errors were assessed. Of late, considerable attention has

been given to the generation of DTMs from contours for regions where elevation data is not available in digital form. This due the fact that contour lines are readily available from topographic maps and the advanced techniques of digitising and scanning graphical input (Vozenilik, 1994). In a series of papers, (Arrighi and Soille, 1999; Vozenilik, 1994; O'Callaghan and Mark, 1984; Brandli, 1992; Peng *et al*, 1996; Ansoult *et al*, 1990; Ebi *et al*, 1994, Wise, 2000; Robinson, 1994; Dakowicz and Gold, 2003; Gold and Dakowicz, 2003), general methodology for the generation of DTM from digitized topographic maps or elevation digitized from topographic maps were presented. Various systems for extracting surface information such drainage networks from digitized elevation data were also presented. The case at hand deals with digitizing contour lines and some points along the contour lines to enable use of the interpolation algorithms as implemented in ESRI ArcGIS software. Three interpolation techniques were compared using visualization of contour data and root mean square error.

The rest of the report discusses the interpolation algorithms used in the project, how the contour map was digitized and, converted to a DTM in a GIS environment, and addresses related accuracy issues. Also results and application examples are discussed. Finally, conclusions and discussions of future research works are outlined.

## 2. DTM GENERATION IN A GIS ENVIRONMENT

DTMs are a major constituent of GIS and they are recently used for 3D GIS analysis. They provide the opportunity to model, analyse and display phenomenon related to topography and other surfaces. Within a GIS, DTMs are most valuable as a basis for extraction of terrain-related attributes and features (Weibel and Heller, 1991) and most GIS researchers often store and manipulate the terrain information directly as a DTM, disregarding the source (Peng *et al*, 2004). DTM also makes possible GIS analysis such as generation of slope, aspect, and watershed drainage data. (Weibel and Heller, 1991; Dakowicz and Gold, 2003; Gold and Dakowicz, 2002).

The relief of the study area is generally undulating with an average height of 850ft above mean sea level. For this research report, mainly ESRI ArcGIS software was used for digitizing the topographic map and also used as a GIS analysis. In order to replicate the map properties of the hard copy map in the output digital contour map, the software requires the creation of a geodatabase within which individual datasets may be created. A geodatabase as implemented in ArcCatalog (component of the ArcGIS software) offers users the opportunity to create datasets and feature classes with their spatial reference and properties assigned and implemented in a unified file system (Peng *et al*, 2004). For this project, one dataset was created within which two feature classes namely contours (polyline) and elevations (points) can be found.

Before digitizing topographic contour map, it was imperative that certain factors and map properties were critically tested in order to produce a digitized topographic contour map which would be compatible with other maps of the same area. In the case of this project the following map properties were identified and tested: map scale (1: 2500); coordinate system (Ghana grid); map units; and grid interval (1000ft). After ascertaining map quality and properties, the control points with which the map will be registered later, were established before digitizing begun.

In all, eight grid intersections, evenly distributed over the map were selected for the purpose of registering the map (i.e., map registration is the process of transforming the coordinate system of a digitizing board into real world coordinates). ArcMap (a module of ESRI ArcGIS software) corrects for any alignment problems when registration is completed and displays such adjustments in an error report. The error report includes two different error calculations: a point-by-point error; and a root mean square error (rmse). The point-by-point error represents the distance deviation between the transformation of each input control point and corresponding point in map coordinates and the rmse is the average of those deviations. The topographic contour map was digitized as polyline and point features respectively. After digitizing, attributes including elevations and contours were added to the point and contour polyline features respectively.

The rmse is reported in both current map units and digitizer inches. In the case of this project the point-by-point error was found to be 1.7958 while the average rmse was 0.008. After the map registration, the two features which were created in the geodatabase were contour polylines (as can be seen in Figure 1) and elevations along the contour polylines (i.e., Figure 2). These were added as layers in the ArcMap environment. Other edits such as double lines and multiple digitizing of points were conducted.

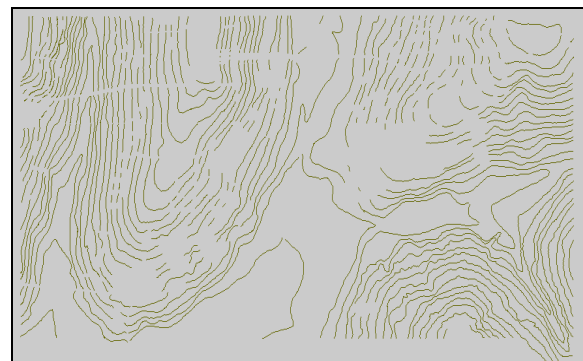


Figure 1: Sample of Digitized Topographic Map



Figure 2: Extraction of Elevation from Contour Lines

### 2.1 Digital Terrain Modelling

The digitized contour data must be structured or formatted to enable handling by subsequent terrain modeling operations and the two most commonly used data formats for DTMs (Weibel and Heller, 1991, Peng *et al*, 2004) are rectangular grid (raster) or TIN (triangulated irregular network). The overwhelming ma-

jority of DTMs conform to one or other of two data structures (Weibel and Heller, 1991).

Grid DTMs as defined in Weibel and Heller (1991), present a matrix format those records topological relations between data points (stored as a two-dimensional array of elevations) and it is inherently constrained to cell size (Peng *et al*, 2004). A TIN DTM, on the other hand, is based on triangular elements, with vertices at the sample points and they record topological relations explicitly. Both the TIN DTM and the grid DTM have their advantages and disadvantages in applications and no data format is clearly superior for all tasks of digital terrain modelling (Weibel and Heller, 1991). In digital terrain modelling, interpolation serves the purpose of estimating elevations in areas where no data exist (Weibel and Heller, 1991). Interpolation is based on the assumption that spatially distributed objects are spatially correlated; in other words, elevation data that are close together tend to have similar characteristics. To create a DTM from 2D contour and elevation observations, TIN model was first generated and then the TIN model was converted to raster format that is DTM. Figure 3(a) shows the nodes and edges of TIN as displayed in ArcGIS whereas Figure 3(b) is a perspective view of a TIN model with nodes, edges and faces.

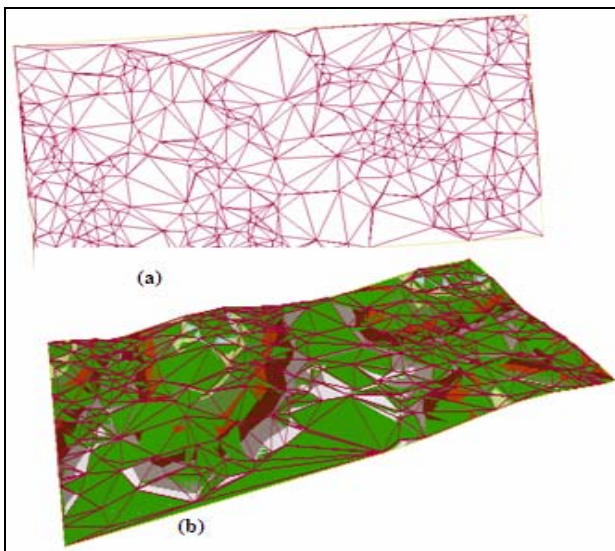


Figure 3: TIN Model of a Set of Terrain Elevations as Displayed in ArcGIS

### 2.1.1 Interpolation Methods for Digitized Contour Data

This paper investigates the quantification of errors within interpolated surfaces. It focuses on comparison of inverse-distance weighted average (IDWA), kriging and natural neighbours, and quantified the inaccuracy using the root mean square error (discussed in Section 2.1.2). Such measure is useful general indicators of error within the surface models (Smith *et al*, 2004). Each method has parameters that can be modified to create a raster that suits particular needs.

IDWA is an estimation method where values at any specified locations are determined by a linear combination of values at sampled points (Gold, 1989). It assumes that each sample point has a local influence that diminishes with distance (Goncalves, 2006). It weights the points closer to the processing cell more heavily than those farther away. In this project, it was specified

that 12 points within a maximum radius of 500ft should be used to determine the value of each output cell. The closer a point is to the center of the cell being estimated, the more influence or weight it has in the averaging process.

Kriging is a geostatistical interpolation technique similar to IDWA which estimates the elevation at grid nodes as a weighted average of the measured elevations at the reference points (Goncalves, 2006). That is, kriging uses the combination of weights at known points to estimate the value at unknown point. It fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. In IDWA, the weight depends solely on the distance to the prediction location. However, in Kriging, the weights are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement among the measured points. As with IDWA, if 12 points were not found before the maximum distance of the radius is reached; fewer points would be used in the calculation of the interpolated cell. For ease of comparison, the same number of points and maximum radius distance were used for the Kriging and IDWA parameters.

Finally, natural neighbour or area stealing uses the Voronoi diagram to define the neighbours of point where the interpolation is needed (Gold, 1989). What is important here is the strategy to select the neighbours of the point to be interpolated and different strategies to select a set of points from the whole dataset to approximate the unknown value (Gold, 1989). Detailed information on natural neighbours with Voronoi diagram and Delaunay triangulation can be found in Gold (1989). Natural neighbour method is most appropriate where sample data points are distributed with uneven density. All interpolation was conducted in ESRI ArcGIS environment and resultant surfaces produced are shown in Figures 4 to 6, and these results are discussed in Section 3.

### 2.1.2 DTM Quality Control

After digitizing contours and points along contours from a topographic map, three interpolation methods have been used to generate DTMs and their accuracies in terms of root mean square errors are assessed in this Section. Quantifying accuracy in DTMs requires comparison of the original elevations with the elevations in a DEM surface which results in elevation differences at the tested points (Smith *et al*, 2004). As stated in Smith *et al*, (2004) the error at each investigated point with the surfaces was considered to be the difference between the raw data point ( $Z_{ri}$ ) and the interpolated value ( $Z_{di}$ ) for that location (See equation 1).

To analyse the pattern of deviation between two sets of elevation data, conventional ways are to yield statistical expressions of the accuracy, such as the rmse, standard deviation (SD), and mean. The most widely used measure is reported simply as the root mean square error of elevation (Robinson, 1994; Smith *et al*, 2003; Smith *et al*, 2004; wise 2000; Weibel and Heller, 1991; Carla, *et al*, 1997). Root mean square error measures the dispersion of the frequency distribution of deviations between the original elevation data and the DEM data, mathematically expressed as:

$$rmse = \sqrt{\frac{1}{n} \sum_{i=1}^n (z_{di} - z_{ri})^2} \quad (1)$$



Where:  $Z_{di}$  is the  $i$ th elevation value measured on the DTM surface;  $Z_{ri}$  is the corresponding original elevation; and  $n$  is the number of elevation points checked. It is known that DTM can vary in quality depending on their method of creation. Three DTMs derived from digitised contours were compared. The rmse and standard deviations (std dev) statistics in each interpolation method were analysed and the results presented in Table 1. These results are discussed in Section 3.

	<i>std dev(ft)</i>	<i>rmse (ft)</i>
<i>Kriging</i>	1.890	1.891
<i>IDWA</i>	4.894	4.894
<i>Natural Neighbour</i>	2.346	2.346

Table 1: rmse and std dev of the three interpolators

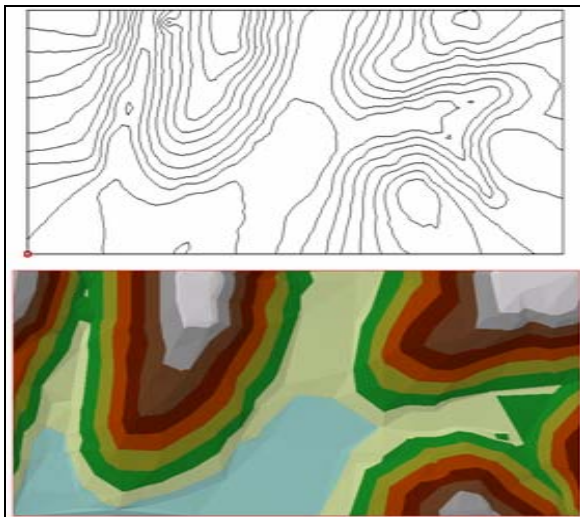


Figure 4: Showing Generated Contour and DTM using Kriging Interpolation Method.

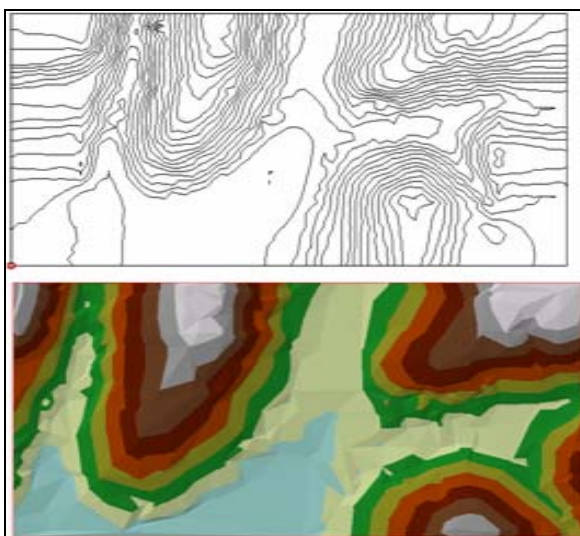


Figure 5: Showing Generated Contour and DTM using IDWA Interpolation Method

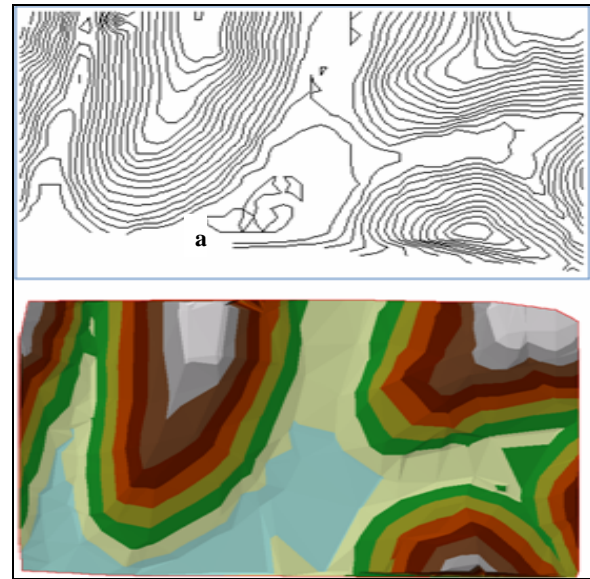


Figure 6: Showing Generated Contour and DTM using Natural Neighbour Interpolation Method

### 3 ANALYSIS OF RESULTS

ArcScene (a module in ESRI ArcGIS software) provides the interface for viewing multiple layers of 3D data for visualizing data, creating surfaces, and analyzing surfaces. The first observation that is made when the various TINs (as shown in Figures 4 to 6) are compared is that the IDWA TIN shows more detail especially in areas where there was a dense cluster of points. This could have resulted from the low power specified. Consequently the local influence diminished with distance therefore weights were more evenly distributed among the closer points and so a more detailed surface was the result.

Of the three categories of contours as produced by three interpolating algorithms, the natural neighbour produces contours (as shown in Figure 6) that are almost as good as the original digitized contours (as shown in Figure 1). However in the portion labelled *a*, (in Figure 6) there is a cluster of contours which is absent in the original digitized contour. This could be due to the sparse data in that portion which led to the method assuming heights from distant points. The Kriging contours (as shown in Figure 4) are fewer and sparsely distributed. The generalized nature of this contour representation was probably caused by the spherical semivariogram model which, by its nature, generates smoother outputs. The IDWA contour representation (as shown in Figure 5) has the steepest contour lines because of the assumption on which the method was based.

From the results in Table1, it was further evident that the different interpolation algorithms had significant effect on the DTM. A rmse of - for instance -1.891 feet, for the Kriging method, implies that, on average, if a measurement is taken from the Kriging surface, it would be in error by 1.891 feet. In the case of the IDWA or Natural Neighbour DTMs, the errors would be 4.894 or 2.345 respectively. It can be seen that the IDWA method was found to produce the lowest rmse. The DTM generated by the Kriging method has the best quality amongst the 3 interpolators because it had the lowest rmse. Unfortunately, DTMs from digitized contourlines can have certain unavoidable quality draw-backs. It is obvious that the

quality of the generated DTM depends on the quality of the contour lines.

As already stated, the problems posed by DTMs generated from contour lines are : the inhomogeneous data distribution in that areas with nearly no points vary with areas of high point density and the loss of characteristic topographic features (ridges, summits, saddles, drainage lines and valleys) during the generation of the DTM. Errors introduced during the production process of the contours such as line drawing, line generalization and reproduction plus the error introduced during contours digitizing affect the quality of the digitized data. The resulting surface models (as can be seen in Figures 4 to 6 ) provide a good representation of the general landscape and contains additional detail information (such as slope, aspect, cross-sections, volumes hillslope) to describe, evaluate and quantify terrain properties. Also, if the digital contours are georeferenced, they can be readily integrated into existing GIS for 3D surface visualization and spatial analysis. Results of intervisibility analysis are presented in subsequent Sections.

#### 4 APPLICATION EXAMPLE- VISIBILITY ANALYSIS

The shape of a terrain surface dramatically affects what parts of the surface someone standing at a given point can see (ESRI, 2006). What is visible from a location is important element in determining the value of real estate, the location of telecommunication towers, or the placement of military forces (ESRI, 2006). 3D Analyst (as in ESRI ArcGIS software) allows visibility to be determined on a surface from point to point along a given line of sight (discussed in Section 4.1) or across the entire surface in a viewshed (as discussed in 4.2).

##### 4.1 LINE OF SIGHT

ESRI (2006) defined the line of sight as a line between two points that shows the parts of the surface along the line that are visible to or hidden from an observer (ESRI, 2006). Creating a line of sight helps to determine whether a given point is visible from another point. If the terrain hides the target point, one can see where the obstruction is and what else is visible or hidden along the line of sight (ESRI, 2006). The visible and hidden segments are shown in Figure 7.

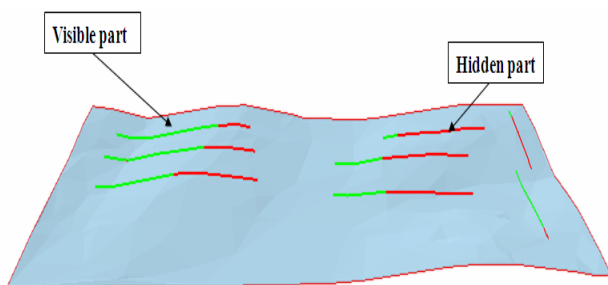


Figure 7: Line of Sight indicating Visibility

In Figure 7, a line of sight (a graphic line between two points on a surface) shows where along the line the view is obstructed. Before the line of sight is created, the observer offset (that is, the eye level of the observer) is used in determining what is visible from the observer's location. For example, an observer with a height of 0—the units are the same as the surface's z-

units— will usually have a more obstructed view than one with a height of 1 or 10 (ESRI, 2006).

Similarly, the target offset (that is the height of the target point above the surface) with a height of 0 are less visible than taller ones. Detailed descriptions of observer and target offsets can be found in ESRI (2006). Considering the check for intervisibility during reconnaissance in Land Surveying project work, the observer offset used in research was 6 feet (because that is the average height of a person) and the target height used was 5 feet (which is the average height of a ranging pole). These same parameters were applied in deriving a viewshed (a discussion follows in Section 4.2).

##### 4.2 VIEWSHED

The viewshed identifies the cells in an input raster (i.e., DTMs derived from the contour) that can be seen from one or more observation points or lines (ESRI, 2006; Sinclair Knight Merz, 2005). Each cell in the output raster receives a value that indicates how many observer points can see the location. If there is one observer point, each cell that can be seen from the observer point is given a value of 1. All cells that cannot be seen from the observer point are given a value of 0 and this equates to knowing the number of observation points that can be seen from each individual cell (ESRI, 2006; Sinclair Knight Merz, 2005). The Viewshed analysis allows the places that can be seen from one or more observation points or lines to be found. If lines are used as input, the observation points occur at the vertices of the lines and if points are used then the observation points will occur at the nodes. As stated earlier, ESRI ArcGIS software was used for this purpose. The input to the modelling process is elevation point data. The observer and target offsets were 6ft and 5ft respectively, for the same reasons as those stated in the creation of line of sight (as discussed in Section 4.1). A viewshed map (as can be seen in Figure 8) contains cells coded to indicate whether they are visible to or hidden from the observer and if there are more than one observer points, each visible cell in the raster shows the number of points from which it is visible. For example, Figure 8 shows the total observation points visible from each individual cells as a colour ramp ranging from light yellow for low visibility, through purple to dark purple for areas of highest visibility (Sinclair Knight Merz, 2005).



Figure 8: Viewshed indicating Visibility

This viewshed is useful when one wants to know how visible objects might be—for example, one may need to know “From which locations on the landscape will the landfill be visible if it is placed in this location (ESRI, 2006)?”, “What will the view

be like from this road?", or "Would this be a good place for a communications tower?". Also, displaying a hillshade underneath elevation and the output from the viewshed gives a very realistic impression of the landscape and clearly indicates the locations that an observer can see from the observation point (ESRI, 2006). This has been employed in such areas as pilot training, scenery viewpoint locations, fire towers locations, and the location of microwave transmission stations in use for the wireless industry.

However, the elevation model may need to be supplemented with a layer of obstructions, such as vegetation heights and buildings. In addition, the elevation model typically makes simplistic assumptions about the curvature or lack of curvature of height profiles along the ray and these affect which cells can be "seen" from the viewpoint. The viewshed also is very sensitive to the choice of viewing height from the viewpoint.

## 5. CONCLUSIONS

In this project, DTMs were generated from points digitized along contour lines. The problems posed by DTMs generated from contour lines are the inhomogeneous data distribution in that areas with nearly no points vary with areas of high point density and the loss of characteristic topographic features (ridges, summits, saddles, drainage lines and valleys) during the generation of the DTM. But, exactly these features determine the quality of a DTM. From the results, the analysis, and the application example, it can be concluded that contours are a good source of deriving representative digital models of terrain.

The resulting surface model provides a good representation of the general landscape and contains additional detail information (such as slope, aspect, cross-sections, volumes hillslope) to describe, evaluate and quantify terrain properties. Also, if the digital contours are georeferenced, they can be readily integrated into existing GIS for 3D surface visualization and spatial analysis. Results of surface analysis (intervisibility analysis) are presented and among other applications, the DTMs proved useful in surface analysis. However, future research will concentrate on investigating the effect of the three (3) interpolation methods at different grid resolutions. This is important because grid resolution affect the representation and accuracy of the generated DTMs. Also, the sampling density along the contourlines will be investigated. The parameters used in the three interpolation methods (kriging, IDWA, and natural neighbours) for deriving the DTMs be varied further and compared using statistical analysis.

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