JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 15 2007

SCALE FACTOR AND DIGITAL ELEVATION ANALYSIS FOR HYDROLOGICAL STUDIES

Chng Loi Kok
Mohammad Firuz Ramli

Faculty of Environmental Studies
University Putri Malaysia
Selangor, Malaysia

The digital elevation model (DEM) is usually used to express a topographic surface in three dimensions and to imitate essential natural geography. The DEM is a model of the elevation surface, which is subject to errors. The Gurun area in Kedah, Malaysia was chosen for study, and the focus was on terrain analysis and the impacts of DEM resolution on topographic attributes related to hydrological studies. Five DEM resolutions were derived and the impact of different resolutions on the topographical parameters related to hydrological studies was compared. The result demonstrated that a fine DEM resolution revealed more detailed topographic values compared to the coarse DEM.

INTRODUCTION

The digital elevation model (DEM) is a computer representation of the earth's surface and it is usually used to express a topographic surface in three dimensions and to imitate essential natural geography. Digital elevation models are used to determine attributes of terrain, such as elevation at any point, slope and aspect features on the terrain, drainage basins and watersheds, drainage networks and channels, peaks and pits and other landforms, modeling of hydrologic functions, energy flux and forest fires. The resolution, or the distance between adjacent grid points, is a critical parameter of a DEM (Klinkenberg, 1990). With higher DEM resolution, the level of detail is increasing and better represented, but the influence of data error is also increased at the same time. With a lower DEM resolution, the impact of data error is decreased, but it will cause more significant error on derived results (Zhou and Liu, 2003). However, a lower DEM resolution will cause loss of topographic characteristics within the cell and will create a smoothing effect during slope estimation (Widayati et al., 2004).

The DEM is a model of the elevation surface, and the data are subject to errors, including systematic and non-systematic errors. Error is the departure of a measurement from its true value. DEM errors are elusive and constitute uncertainty (Wechsler, 1999). There have been many studies conducted that displayed errors such as error sources, error testing, error visualization, error correction, and other aspects of DEM error. One of the problems faced by many DEM users is choosing the appropriate DEM resolution. In general, an increase in the detail in DEM means more accurate terrain parameters. This increase, however, depends on the general variability of the landscape (Hengl, 2006) because high resolution is unnecessary for a smooth landscape. Thus, numerous studies have been reported on the accuracy analysis of terrain (Takagi, 1998; Wechsler, 1999; Thompson et al., 2001; Zhou and Liu, 2004; Kienzle, 2004; Widayati et al., 2004; Lassueur et al., 2006; Smith et al., 2006; and Ziadat, 2007) and hydrological modeling (Walker and Willgoose, 1999; Kenward et al., 2000; Horritt and Bates, 2001; Maathuis, 2006; Wechsler, 2006) in relation to grid resolution or grid cell size. Those results show that the horizontal and vertical resolutions of DEM have rather obvious effects on terrain attributes based on DEM (Bi et al., 2005). However, selection of the right pixel size will remain an issue that is relative to application type and project objectives (Hengl, 2006).

In hydrological studies, terrain analysis is used to extract information from digital elevation models (DEMs) relevant to overland flow, stream flow and topographic attributes. DEMs represent the topography in a raster data structure (or a grid format). The routing of water over a surface is closely tied to surface form. Flow direction is derived from slope and aspect. From flow direction, the upslope area that contributes flow to a cell can be calculated, and from these maps, drainage networks, ridges and watershed boundaries can be identified. Topographic, stream power, radiation, and temperature indices are all secondary attributes computed from DEM data (Wilson and Gallant, 2000).

This main aim of this study is to determine the potential impacts of using different DEM resolution on terrain and hydrological factors in Gurun, a district in Kedah, Malaysia. Understanding the impacts of different DEM resolutions will increase awareness among users on the effect of the DEM resolution for hydrological studies.

METHODOLOGY

The study area is located at Gurun, one of the districts in Kedah, in Malaysia (Figure 1) Gurun was chosen as the study area because of its variety of terrains including different steepness of slopes, undulating surfaces, and flat areas.

A digital topographic map scaled 1:25,000 of the study area was obtained from Department of Survey and Mapping, Malaysia (JUPEM). The DEM of the study area was derived by creating a triangulated irregular network (TIN). By using the TIN, slope and aspect were derived with 5 different resolutions namely 10m, 20m, 30m, 40m, and 50m (Figure 2). From the different resolution cell size of slope and aspect, the themes were then reclassified into different small classifications. The acreage of the cell for different classification was calculated to compare among 5 different resolutions of cell size. For watershed analysis, a grid map of the TIN was created based on the similar 5 different resolutions of cell size as slope and aspect. Sinks in the grid map were filled and flow direction of the filled sink was derived. Flow accumulation was derived from the flow direction and later was reclassified.

In the determination of the flow direction, the most common algorithm, the "D8" algorithm was employed to interpret the DEM. The "D8" algorithm showed where the flow direction for every cell within the watershed is determined by considering the surrounding eight neighboring cells (Figure 2). The local slope in each of the eight directions of these neighboring cells was calculated by taking the difference in elevation indicated by the DEM value at each of these eight neighboring locations and the value at the cell being examined. Once flow directions were determined, this information was used to determine the flow accumulation. The flow accumulation can also be described as the drainage area. Flow accumulation indicates the total drainage the cell received from any of the eight immediate neighboring cells.

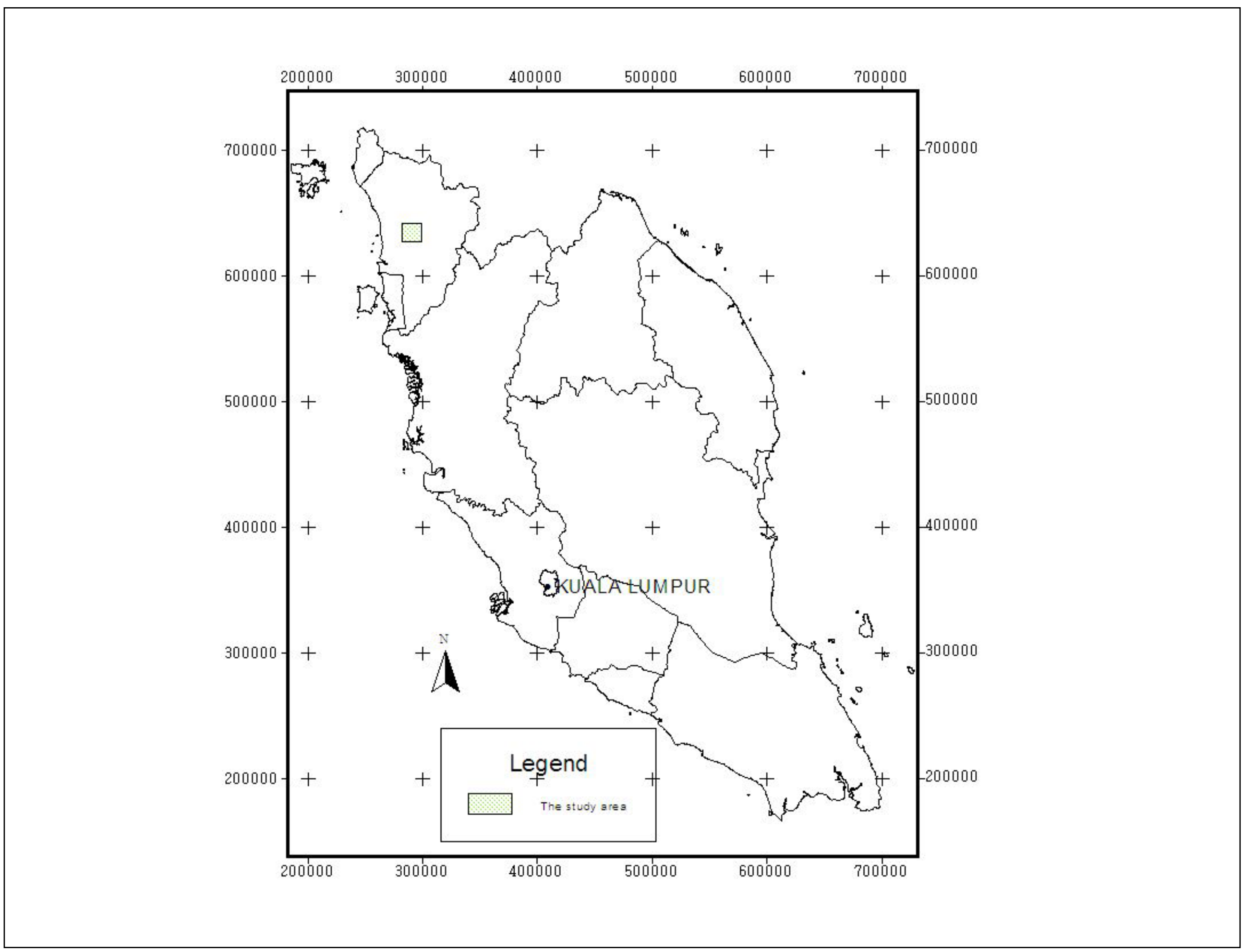

Figure 1. The study area.

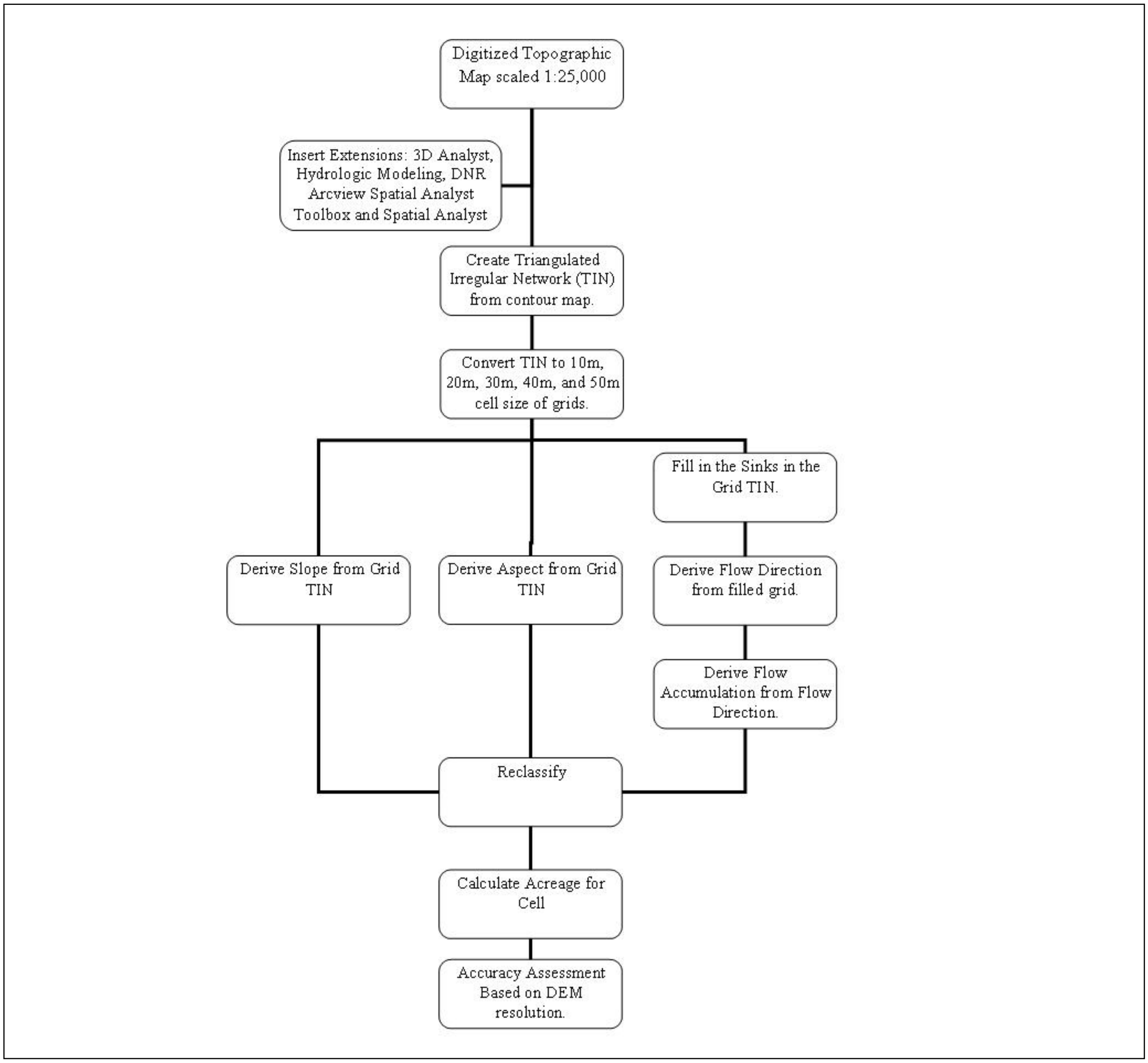

Figure 2. Schematic diagram of study methodology.

RESULTS

Slope

The parameters of the maximum slope, average slope, and standard deviation (SD) are different with different DEM. However, the value of the min slope remains unchanged which is 0^o from resolution 10 m to 50 m (Figure 3). While for max slope, the slope decreases from 86.00^o to 80.47^o at 30m resolution and keeps decreasing to 67.96^o at 50 m resolution. Average slope or mean slope is slightly decreased from 9.46^o at 10 m resolution to 8.80^o at 50 m resolution. The study also shows that the standard deviation of a fine resolution such as 10 m is higher than the coarser resolution or 50 m resolution.

Since the min slope remains unchanged at different resolutions, there is a possibility that min slope not affected by resolution. However, the max slope decreases when the resolution changes from fine to coarse which indirectly causes the mean slope of the study area to decrease. Thus, the computed slopes of the study area tend to be steeper in fine resolution (10m) compared to the

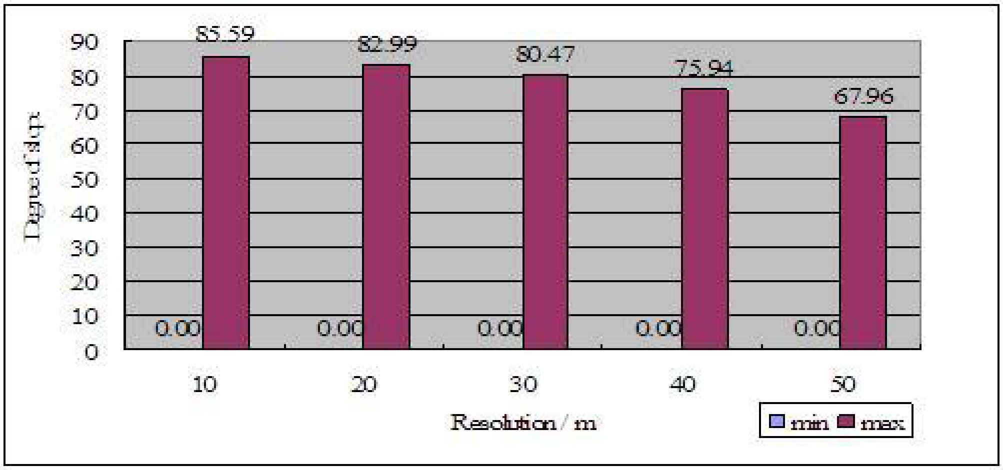

Figure 3. Changes of min and max of slopes at different DEM resolution.

coarse resolution (50m) (Figure 4). Bi et al. (2005) stressed that fine resolution can represent a more accurate real surface and it is clear that coarse DEM resolution underestimates local average slope. The higher standard deviation for fine resolution compared to the coarse resolution is mainly because the higher the resolution, there more details are revealed. The increase of cell size (coarser resolution) to some extent could bring smoothing effects (Widayati et al., 2004) which could lower the standard deviation.

The impacts on the different DEM resolution on slope ranges can be classified as 3 types. For the lower slope range between 0-20º, the area under this slope range increases when the resolution becomes coarser (50m). When the area under the lower slope range increases, it means the flat area increases, causing the computed slope based on DEM to become gentler than the actual slope. In this case, the slope has been underestimated. For the medium slope range between 20-35º, the area under this slope range decreases when the resolution becomes coarser (50m). When the area under the medium slope range decreases, it means the computed slope based on the DEM becomes steeper than the actual slope. Thus, the slope has been overestimated. For upper slope ranges more

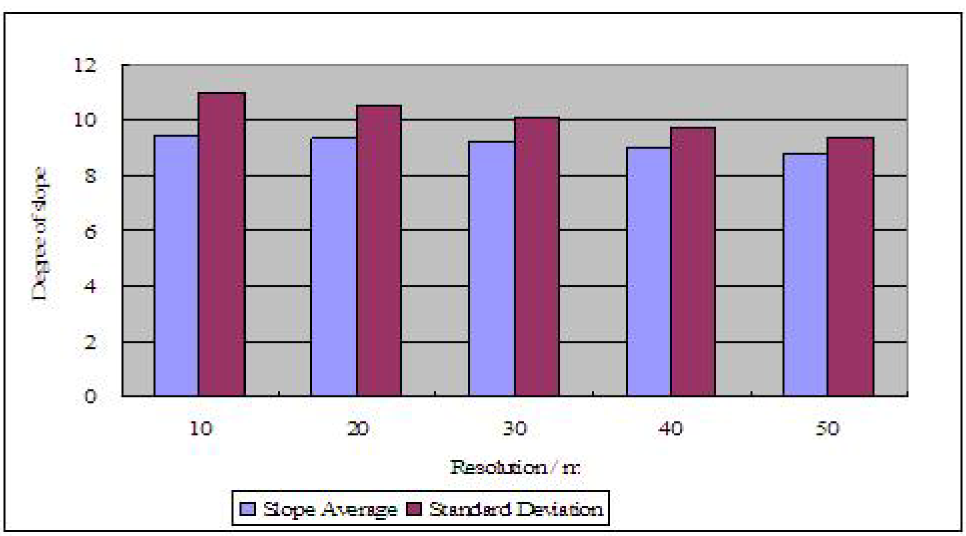

Figure 4. Mean and standard deviation of slope at different DEM resolution.

than 35°, the impact is minimal and differences are too little and usually are ignored. This slope range has fewer impacts from DEM resolution compared to the lower and medium slope ranges. Similar results show in the study carried out by Thompson et al. (2001) where decreasing resolution of a DEM from 10m to 30m tended to create a smoother, less defined landscape, with more moderate slope gradients and reduced curvatures.

Aspect

The impacts of DEM resolution on aspect showed that the percentage area of the each aspect or direction had some incremental effect, while the percentage area of flat area decreased when resolution changed from fine to coarse (Figure 6). When the resolution becomes coarser, the smoothing effects of the cell (Widayati et al., 2004) occur at the slope area which will lower the slope degree and expand slope area at the same time. Thus, the flat area decreases because the overall slope area has increased after the smoothing effects took place when the resolution becomes coarser. The impacts of the resolution on the slope area are greater compared to the impacts on flat area, because slope area is sensitive to the change of resolution. Wechsler (1999) found that uncertainty in the DEM is manifested in higher elevations and steeper slopes on the slopes and elevation maps.

Flow Direction

The impacts of resolution on the flow direction does not change too much from fine to coarse resolution (Figure 7). Most of the flow direction remains unchanged or stable, except the south, west, and north flow directions had some variances compared to the other directions. South flow direction increased 3337.32 acres of area while west and north flow direction decreased 1515.63 acres and 1858.23 acres of area when the resolution decreased from fine to coarse. The other flow directions only vary below 1000 acres when the resolution decreases (Figure 7). The change in area happens when the resolution decreases, and creates a smoothing effect (Widayati et al., 2004) on the slopes. Some of the slope becomes gentler after the smoothing effect and this contributes to the changes of flow direction in the slope. According to Mouton (2005), as the DEM resolution increases, D8 model sensitivity also increases. Haile and Rientjes (2005) showed that the use of DEM's with increasing coarser resolutions may result in different hydraulic gradients and the boundary location and thus dissimilar simulation results.

Figure 5. Percentage area of slope.

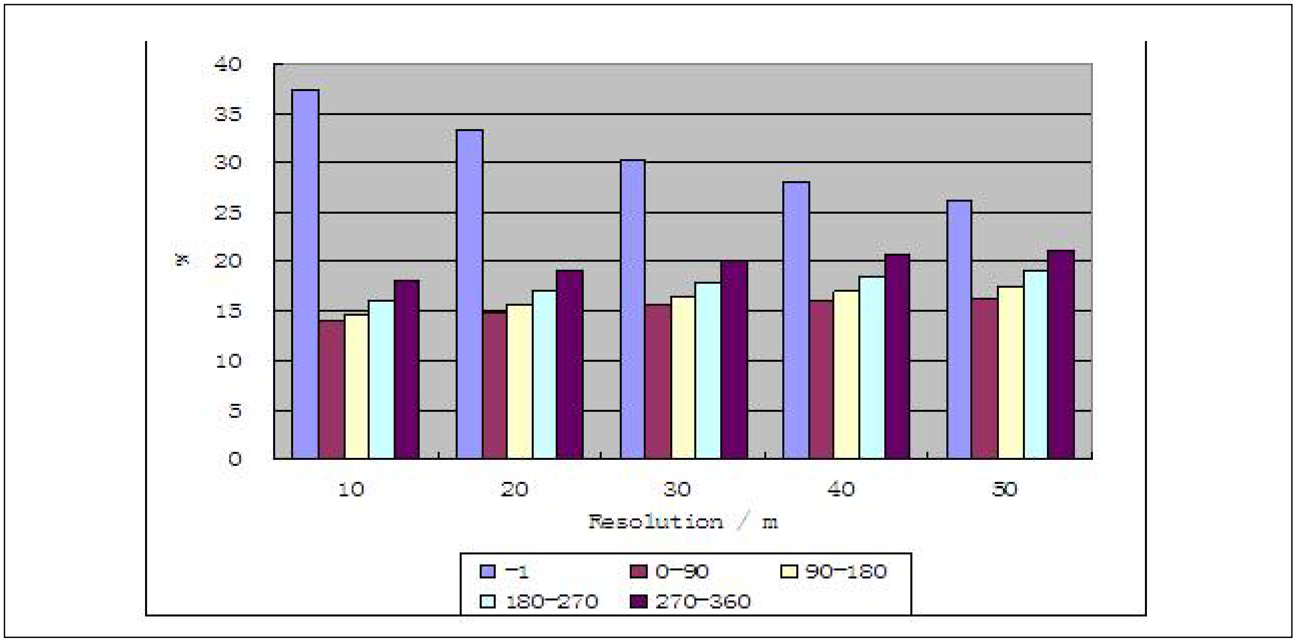

Figure 6. Percentage area of aspect at different DEM resolution.

Flow Accumulation

Compared the impacts that resolution brings to the flow direction, the impacts on flow accumulation are enormous and obvious. The impacts on flow accumulation derived from different DEM resolutions show that the majority of the flow accumulation value including max flow accumulation, average flow accumulation, and standard deviation, receive impacts when the resolution decreases from fine to coarse (Figure 8). Only min flow accumulation remains the same value which is 0 m^2. On the other hand, the max, average, and standard deviation flow accumulation decreases tremendously when the resolution changes from fine to coarse. The decrease rates for these three values are more then 50%.

Max flow accumulation decreases 95% when DEM resolution decreases from 10m to 50m resolution (Figure 8). High DEM resolution enables obtaining more values. In other words, the

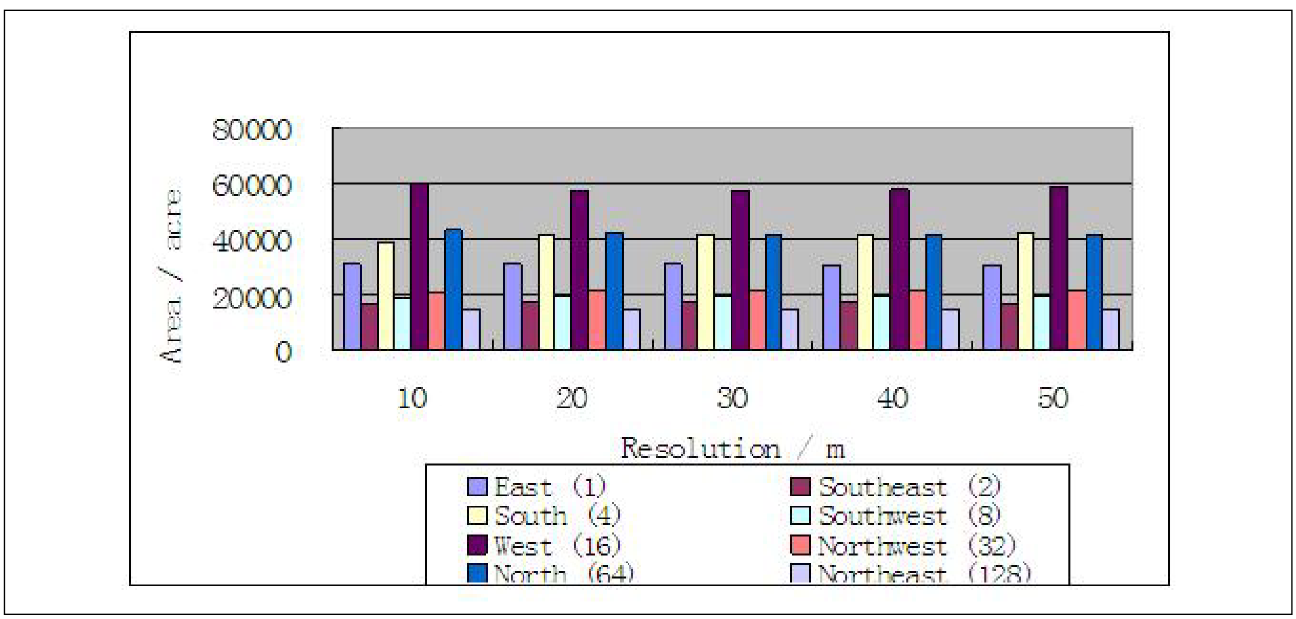

Figure 7. Area of flow direction at different DEM resolution.

higher the value of max flow accumulation, the more river or water bodies are derived from the DEM. Smaller grid cell sizes will allow better representation of complex topography and these high resolution DEMs are better able to refine characteristics of complex topography (Wechsler, 2006). If topography is complex, greater discrepancies can be expected between grid cells. Over small distances, the surface would appear highly variable, but at larger distances, measured slopes would be very similar regardless of where they were measured (Warren et al., 2004). This explains how, in low DEM resolutions, the slope becomes similar or a smoothing effect occurs in the measured slopes. As a result, most of the values in low DEM resolution are smoothed to the majority flow accumulation value, causing the 95% decrease of flow accumulation in the slope measured.

The mean flow accumulation decreases 80% when the DEM resolution decreases from fine to coarse resolution (Figure 9). This is caused by the max flow accumulation which decreases tremendously when the DEM resolution decreases. Mean flow accumulation depends on the min and max flow accumulation derived from the DEM. Since min flow accumulation remains unchanged at 0 m^2 when the DEM resolution decreases, mean flow will now depend on the max flow accumulation obtained.

Fine DEM resolution has been found to have the highest standard deviation of flow accumulation, compared to the other coarser DEM resolutions (Figure 10). Higher DEM resolution resulted in higher values of standard deviation because fine resolution reveals more data in grid cells, causing more variables to occurs in a single grid cell. Sharp images and characteristics of the grid cells was obtained through using fine DEM resolution compared to the coarser DEM resolution, where the slopes are smoothed and the value of the flow shares the same characteristic within the same grid cells.

The area of flow accumulation under different DEM resolutions (Table 1) showed that the DEM resolution also contributes impacts to the area of flow accumulation. Areas of flow accumulation are classified into five classes which represent five categories of flow accumulation.

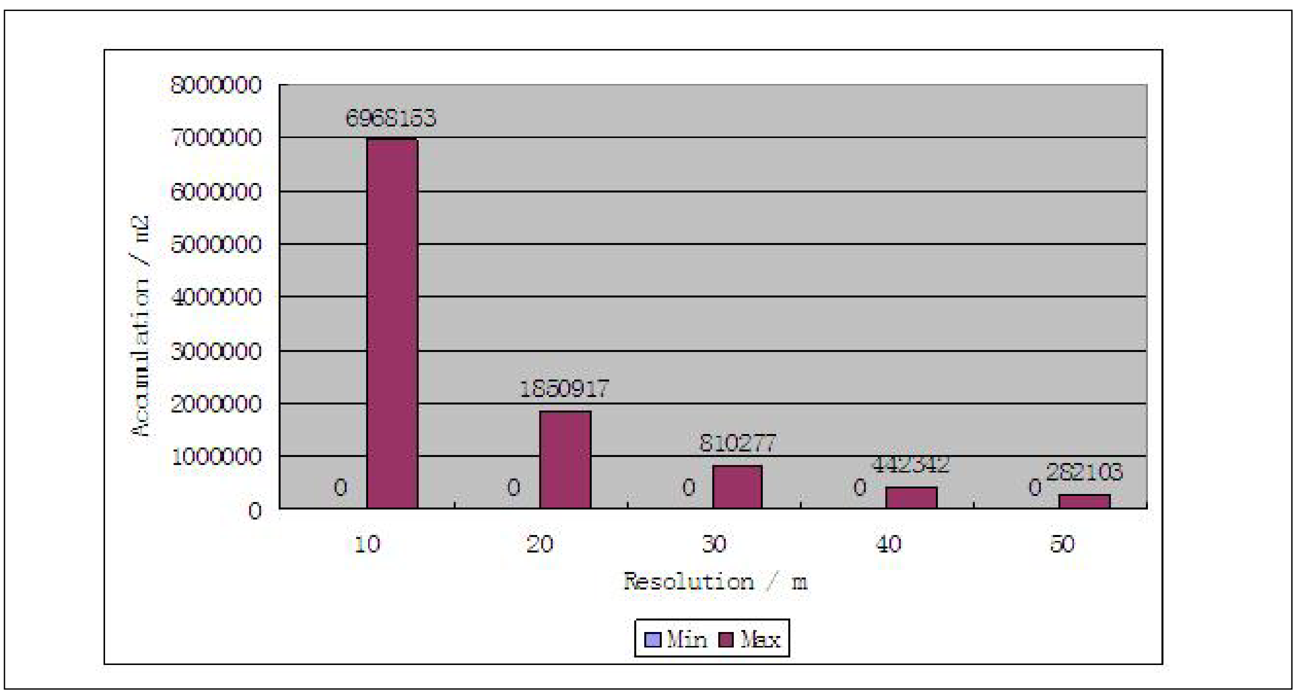

Figure 8: Min and max of flow accumulation at different DEM resolution.

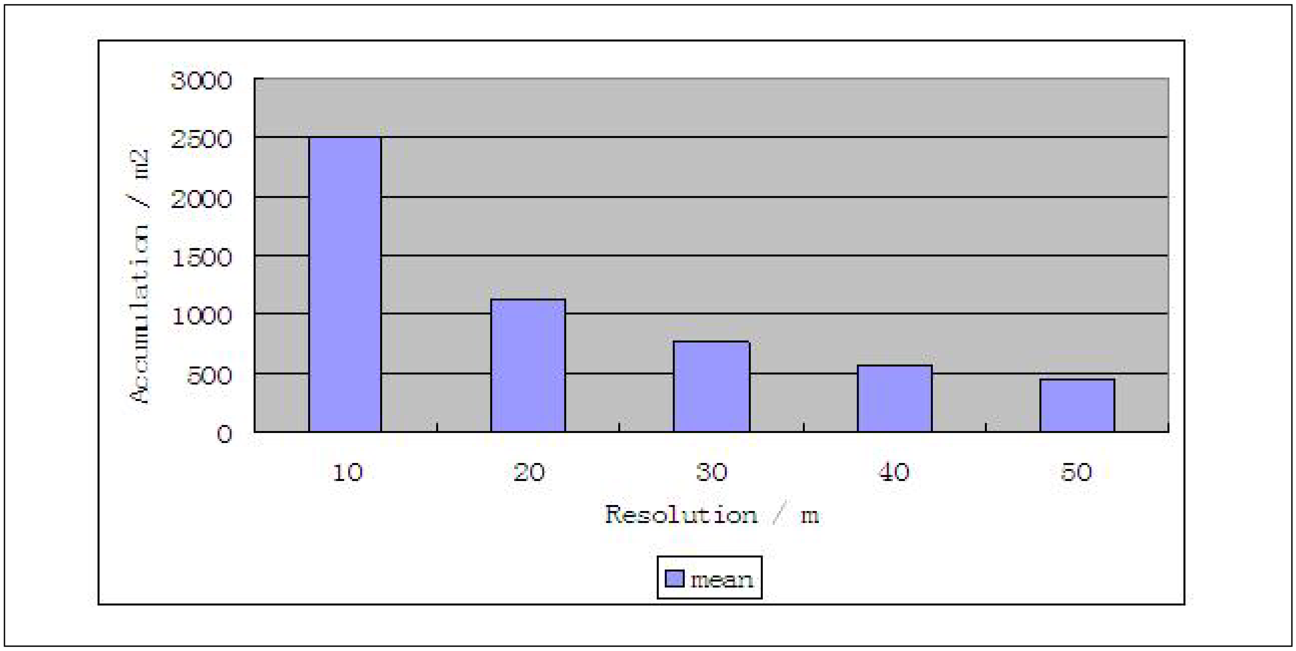

Figure 9. Mean flow accumulation at different DEM resolution.

In class 0-$10^3$$m^2$, the areas of flow accumulation had increased 775 acres when DEM resolution decreased from 10m to 50m. This category usually applies on the land surfaces and small water bodies that represent less than $10^3$$m^2$ of area in the grid cells. These small water bodies or rivers increase when DEM resolution increases. This indicates that the land surface computed decrease is due to increasing river lines and river networks. In high DEM resolution, more characteristics of the study area are revealed compared to in the low DEM resolution where most of the data are generalized because of the smoothing effect at the slopes. The other three categories of accumulation area ranging between $10^3$$m^2$ and $10^6$$m^2$ had a stable increment in area when changed to high DEM resolution. However, the final category of the flow accumulation range, $10^6$$m^2$ to

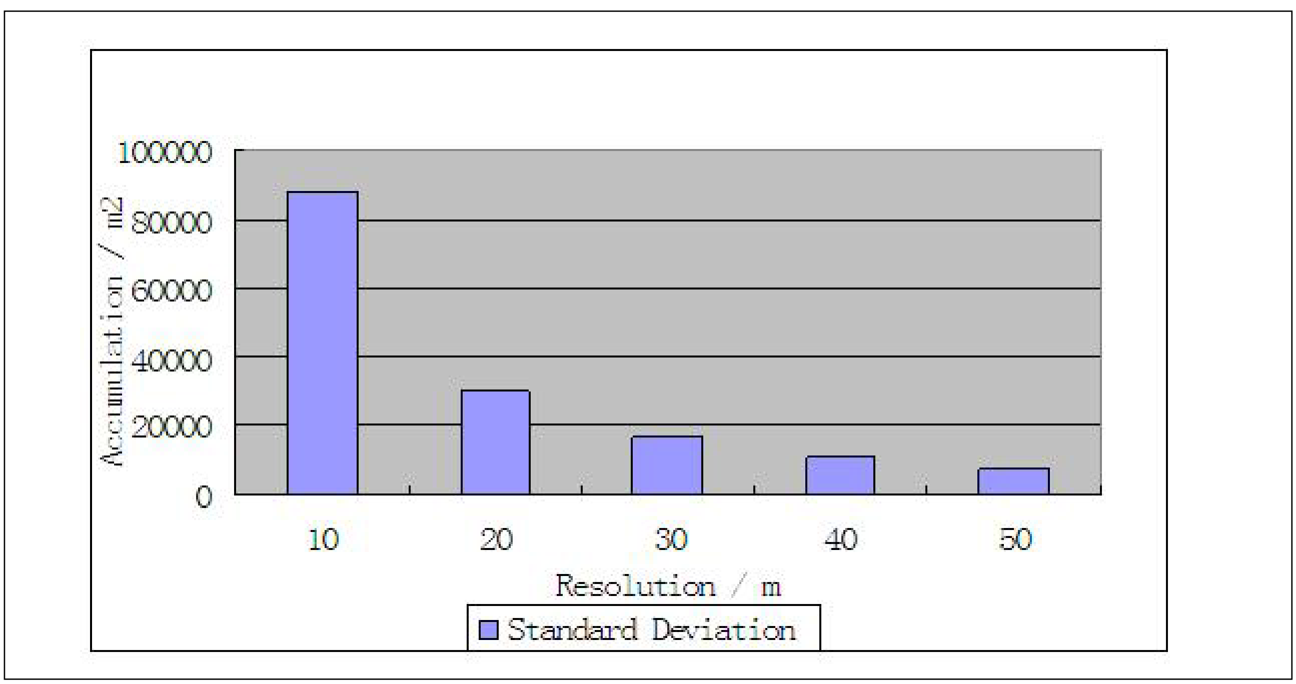

Figure 10. Standard deviation of flow accumulation at different DEM resolution

Table 1. Area of flow accumulation.

Flow Accumulation / m^2	Resolution / m				
	10	20	30	40	50
$0\text{-}10^3$	237864.36	238621.96	238452.37	238694.51	238639.40
$10^3\text{-}10^4$	4034.86	3386.41	3397.28	3561.06	3750.42
$10^4\text{-}10^5$	1068.13	1227.12	1077.94	885.62	897.61
$10^5\text{-}10^6$	377.28	283.77	430.11	431.74	284.17
$10^6\text{-}10^7$	164.99	52.88	0.00	0.00	0.00

10^7m^2, does not show any value in low DEM resolution (30m, 40m, 50m) and starts to show some value in 20m DEM resolution and increases to 164.99 acre of area in 10m DEM resolution. The reason there was no value in 30m, 40m, and 50m DEM resolution is because the coarse DEM resolution has caused smoothing effects on the flow accumulation. In smoothing effects, the minor flow accumulation values will overridden by the major flow accumulation data. Thus, there is no value revealed in this category with coarse resolution. Max flow accumulation (Table 1) also showed that the max flow accumulation in 30m, 40m, and 50m DEM resolution is absent in the category.

DISCUSSION

A Digital Elevation Model is crucial for analyzing terrains. Many of the terrain attributes such as slope, aspect, flow direction and flow accumulation can be derived from a DEM. These attributes play a significant role in hydrological processes, soil erosion control, flood modeling, urban drainage planning and other land-use planning.

Both the average slope and standard deviation decrease with coarser DEM resolution. Max slope also decreases in coarser DEM resolution but the min slope remains unchanged at 0^o. Meanwhile, the different impacts of DEM resolution to slope range can be classified into three categories, which are $0\text{-}20^o$ where the slope is underestimated; $20\text{-}35^o$ where the slope is overestimated; and 35^o and above with minimal impacts from DEM resolution. For slope aspect, the study showed that there was some increase in all aspect when the DEM resolution become coarser, but it is not significant. However, flat areas do decrease when DEM resolution becomes coarse due to smoothing effects that expand the area of slopes. In hydrological analysis, the impact of DEM resolution on flow direction is not significant where only a few directions had some variance, whereas changes in other directions are too small and are ignored. In flow accumulation, max, mean and standard deviation of flow accumulation decrease rapidly when the DEM resolution becomes higher. The area under the flow accumulation showed the river network to become more complex due to increase of river lines. The river lines under the categories above 10^3m^2 of flow accumulation area increase when the resolution becomes higher.

Digital Elevation Model resolution is an important key element in deriving terrain attributes. It significantly influences values of terrain attributes. It has great impact on the slopes and hydrological system. A slight alteration in the DEM resolution may produce a totally different result. Since DEM with fine resolution can more accurately represent real land surfaces (Bi et al., 2006), it has led many DEM users to seek the highest DEM resolution possible, through increasing cost associated with both data acquisition and processing (Wechsler, 2006).

CONCLUSIONS

It is clearly shown in this study that a higher DEM resolution will result in less smoothing effect and will increase the detail of the topographical expression. Higher resolutions will produce more accurate results for the terrain attributes.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Ghufran Redzwan and Dr. Helmi Zulhaidi Mohd Shafri for their constructive comments.

REFERENCES

Bi, H., X. Li, M. Guo, X. Liu, and J. Liu. 2006. Digital Terrain Analysis Based on DEM. Journal of Beijing Forestry University, 27(2). (in Chinese).

Haile, A.T., and T.H.M. Rientjes. 2005. Effects of LiDAR DEM resolution in flood modeling: a model sensitivity study for the city of Tegucigalpa, Honduras. ISPRS WG III/3, III/4, V/3 Workshop "Laser scanning 2005". Enschede, Netherlands. 12-24 September 2005.

Hengl, T. 2006. Finding the right pixel size. Computers & Geosciences, 32, pp. 1283-1298

Horritt, M.S., and P.D. Bates. 2001. Effects of spatial resolution on a raster based model of flood flow. Journal of Hydrology, 253, pp. 239-249.

Kenward, T., D.P. Lettenmaier, E.F. Wood, and E. Fielding. 2000. Remote Sensing of Environment, 74, pp. 432-444.

Kienzle, S. 2004. The effect of DEM raster resolution on first order, second order and compound terrain derivatives. Transaction in GIS, 8(1), pp. 83-111.

Klinkenberg, B. 1990. Digital Elevation Models. National Centre for Geographic Information Analysis Unit 38. http://www.geog.ubc.ca/courses/klink/gis.notes /ncgia/u38.html#UNIT38. Accessed on 12 March 2007.

Lassueur, T., S. Joost, and C.F. Randin. 2006. Very high resolution digital elevation models: Do they improve models of plant species distribution? Ecological Modelling, 198, pp. 139-153.

Maathuis, B.H.P. 2006. Digital elevation model based hydro-processing. Geocarto International 21(1), pp. 21-26.

Mouton, A. 2005. Generating stream maps using LiDAR derived digital elevation models and 10-m USGS DEM. http://www.ruraltech.org/pubs/theses/mouton/ index.asp. Accessed on 12 March 2007.

Smith, M.P., A.X. Zhu, J.E. Burt, and C. Stiles. 2006. The effects of DEM resolution and neighborhood size on digital soil survey. Geoderma, 137, pp. 58-69.

Takagi, M. 1998. Accuracy of digital elevation model according to spatial resolution. International Archives of Photogrammetry and Remote Sensing, 32(4), pp. 613-617.

Thompson, J.A., J.C. Bell, and C.A. Butler. 2001. Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil-landscape modeling. Geoderma, 100, pp. 67-

Walker, J.P., and G.R. Willgoose. 1999. On the effect of digital elevation model accuracy on hydrology and geomorphology. Water Resources Research, 35(7), pp. 2259-2268.

Warren, S.D., M.G. Hohmann, K. Auerswald, and H. Mitasova. 2004. An evaluation of methods to determine slope using digital elevation data. Catena, pp. 58, 215-233.

Wechsler, S.P. 2006. Uncertainties associated with digital elevation models for hydrologic applications: a review. Hydrology and Earth System Sciences Discussions, 3, pp. 2343-2384.

Wechsler, S.P. 1999. Digital elevation model (DEM) uncertainty: Evaluation and effect on topographic parameters. ESRI User Conference 1999 Proceedings. http://gis2.esri.com/library/userconf/proc99/proceed/papers/pap262/p262.htm Accessed on 12 March 2007.

Widayati, A., B. Lusiana, D. Suyamto, and B. Verbist. 2004. Uncertainty and effects of resolution of digital elevation model and its derived features: case study of Sumberjaya, Sumatera, Indonesia. Int. Arch. Photogrammetry Remote Sensing, 35(B4), pp. 1013-1018.

Wilson, J.P., and J.C. Gallant. 2000. Chapter 1: Digital terrain analysis. In J.P. Wilson and J.C. Gallant. Terrain Analysis: Principles and Application. John Wiley and Sons, New York. pp. 1-27.

Ziadat, F.M. 2007. Effect of contour intervals and grid cell size on the accuracy of DEMs and slope derivatives. Transactions in GIS, 11(1), pp. 67-81.

Zhou, Q., and X. Liu. 2004. Analysis of errors of derived slope and aspect related to DEM data properties. Computers & Geosciences, 30, pp. 369-378.

ADDRESS FOR CORRESPONDENCE
Mohammad Firuz Ramli
Faculty of Environmental Studies
University Putri Malaysia
43400 Serdang, Selangor
Malaysia

Email: firuz@env.upm.edu.my