Size <u>does</u> matter: relationships between image pixel size and landscape process scales

C.F. Pain

CRC LEME, c/o Geoscience Australia, PO Box 378, Canberra ACT 2601, email: colin.pain@ga.gov.au

Keywords: *image pixel size; digital elevation models; landscape processes.*

EXTENDED ABSTRACT

This paper briefly reviews the application of digital elevation models (DEMs) to the study of landscapes. Such studies can involve both the enhancement of DEM images to highlight particular patterns, and the use of DEMs to model attribute values of landscapes. Recognition of palaesurfaces is an example of the first use, while modelling hydrological properties based on slope attributes derived from a DEM is another.

Following the review, the paper presents work on the character and scale of slopes and the processes that form them in a study area near Picton, NSW. These slope and process scales are then considered in the context of digital elevation models as a source of data about slopes.

Slope angles are clustered around modal values that may be referred to as characteristic and threshold slopes. Characteristic slopes are those most commonly occurring in an area, and their inclination is controlled by the material on which they are formed and the processes that control their formation. They are closely related to threshold slope angles, which are those where sudden changes of slopes processes take place.

Most DEMs have generalisations of the land surface built into them. If these generalisations are within the spatial range of the processes that are operating in the landscape of interest, there is no problem. However, if the generalisations are greater than the resolution of landscape processes, any results or indices derived from DEMs must be treated with caution.

In the Picton study area only an original ground survey and to a lesser degree a 25m “DEM” give any indication of the shape of the ground surface. 50m and 100m DEMs barely resemble the ground surface, and values derived from these latter DEMs in no way reflect the original slope form. Moreover, they give no indication of the characteristic slope values, so they do not reflect the nature of the processes operating in this landscape. A SRTM 90m DEM over the same profile line similarly provides no real ground surface information.

This study shows that, although DEMs are frequently used to derive values for slope angles, the accuracy of these derived values depends on the pixel resolution of the DEM from which they are derived. That accuracy of slope angle and shape depends on DEM resolution is obvious. What is not so obvious, and in many cases seems to be ignored, is that DEM resolution must be better than landsurface process scale if DEMs are to be used to predict spatial patterns of, say, soil attributes.

Slope angles derived from most available DEMs are therefore limited as descriptions of real landscapes and processes unless the data are at a resolution that equals or is better than the scale of slope and regolith processes. The appropriate scale for a particular landscape can only be determined by geomorphic analysis of landform shape and processes; in most cases this will mean ground survey.

In the Picton area a pixel resolution of 5m is adequate to capture the scale of surface processes and therefore likely variation of, say, soil attributes. In other areas the resolution required may be as small as 1m or as large of 100m. In other words, landscape process scale will dictate useful pixel resolution scale.

And although this paper does not consider other raster image data, the results imply that the same conclusions apply to them as well.

1. INTRODUCTION

Image data are now a common input to Geographic Information Systems that are used to describe and model a variety of landscape attributes. In describing, explaining and predicting landscape attributes it is essential to understand the scale at which landscape-forming processes act. This paper presents information about slope angles and their importance as a landform attribute. In particular, it considers the scale of slopes, and parts of slopes, and the processes that form them, with reference to a study area near Picton, NSW. These slope and process scales are then considered in the context of digital elevation models (DEMs) as a source of data about slopes. The purpose is to demonstrate from real slope data that it is critical to have a DEM pixel resolution equal or better that the scale of landscape processes, especially if these processes are to be modelled using a DEM.

The paper begins by providing a brief review of ways in which DEMs have been used to describe and characterise landscapes, and then presents an example involving DEMs and slope processes. This paper restricts discussion to the use of DEMs, but the principles are applicable to other kinds of image data from airborne and space-borne platforms.

2. DEMs AND LANDSCAPE ANALYSIS

There are two main ways in which DEMs have been used in landscape studies. These are now briefly introduced.

2.1. Landscape patterns from DEMs

DEMs may be used to recognise patterns that are present in hill shaded or elevation-sliced images. In some cases simple filters that emphasis slope steepness or aspect are used. Some of the manipulations may be quite complex, but the resulting images are used for subjective identification of patterns and features.

Harrington et al. (1982) provide an early example of the use of a DEM to characterise features of continental scale in Australia. The DEM was gridded from the elevations of gravity stations throughout Australia, and had a spatial resolution of about 6 minutes of latitude and longitude. As DEMs of other countries became available, regional descriptions of landforms based on them began to appear. For example, in Sweden Elvhage and Lidmar-Bergstrom (1987), and Lidmar-Bergstrom et al. (1991) were able to map palaeosurfaces and show relationships between landforms and geology on a 500m gound resolution DEM derived from survey data. Thelin and Pike (1991) showed that an 800m pixel DEM of the USA had a similar capability. This approach has been continued to the present (e.g. Johansson 1999, Jordan et al. 2003, and Kuhlemann et al. 2005), with Smith and Clark (2005) providing an assessment of image visualization techniques.

2.2. Modelling from DEMs

DEMs are also used to generate landscape attributes such as slope angle as inputs into models that predict, for example, particular soil characteristics. Much relevant work is contained in Wilson and Gallant (2000a), a collection of papers devoted to terrain analysis. In their contribution to this volume Wilson and Gallant (2000b) provide a table of attributes that can be computed from DEM data that includes such things as slope angle and length, and profile curvature. DEMs have also been used to provide indices for such things as valley bottom flatness (Gallant and Dowling 2003), and surface and subsurface water accumulation (Roberts et al. 1997, Summerell et al 2004). Another application is that of O'Neill and Mark (1987), who used DEMs to study slope frequency distributions in different climate and geological regimes.

Many modelling studies use a DEM combined with other image data. For example Pickup and Marks (2000) combine a DEM and radiometric data to identify large-scale erosion and deposition processes in the eastern highlands of Australia. They use a 100m grid cell, and recognise the problems of such coarse resolution.

Fryer et al. (1994) asked if earth scientists are fully aware of the limitations of DEMs, and note that errors in a DEM will propagate through to model predictions. Problems with DEM accuracy, both spatial and in elevation, are well documented in the literature. Moore et al. (1991), for example, discuss the quality of DEMs produced by various methods, so problems with DEM accuracy are well known. It is necessary to take into account the origin of the data in DEMs. Many DEMs are derived from the contours and spot heights on topographic maps. A DEM derived from, say, a map with a 20m contour interval, will have a ground resolution unlikely to be better than 20m, no matter what the grid size of the DEM. That is to say, on hill slopes of 45^o the ground resolution of the DEM will be 20m, but because most slopes, at least in Australia, are much gentler that that, the ground resolution will in reality be greater than 20m. Examples of the use of DEMs derived from contour maps include O'Neill and Mark (1987) and Montgomery (2001), neither of whom mentions the contour interval of the maps.

DEMs derived from point measurements such as radar, GPS, or profile laser altimeters may be better in this regard, but allowances must be made for the nature of data collection. For example, resolution along-track may be a few metres, but the tracks may be 100m apart. Light Detection and Ranging (LIDAR) is one of the few systems that collects data from all points, and also has the potential to produce DEMs with 1-2m resolution. Digital photogrammetry (e.g. Lin and Oguchi 2004) also has the ability to produce very high resolution DEMs.

The issue of scale in the context of indices derived from image data has been mentioned in some papers. For example Bende et al. (1995) discuss up-scaling of point measurements of water chemistry to spatial distribution and dynamics of hydrological response units. Gallant and Hutchinson (1996) point out that the grid resolution of DEMs can profoundly influence the spatial patterns of attributes derived from them, and also influence models built from these attributes. Wilson and Gallant (2000b, p. 1) note that "additional work is required to identify the important spatial and temporal scales and the factors that influence or control the processes and patterns operating at particular scales".

Schoorl et al (2000) also note that numerical values of attributes derived from DEMs differ considerably with DEM resolution. For example, they showed that modelled soil loss increased with coarser resolutions. In another example, Warren et al. (2004) compared slopes measured in the field with those derived from DEMs, and found that higher resolution DEMs (1m) produced much better results that lower resolution DEMs (12m). They commented that this variation can lead to widely varying estimates of environmental factors such as soil erosion. Claessens et al. (2005) make similar comments with regard to DEM resolution and landslide hazard modeling.

Some workers (e.g. Park and van de Giesen 2004) show that high resolution DEMs, in their case 5m, can be used successfully to divide hill slopes into representative hydrological domains.

Guth (2003) looked at DEMs over a whole range of scales from global to local. He found that average slope values, for example, increased as the DEM grid size decreased. This is a result of larger pixel sizes generalising slope values and giving lower than "real" values. Others (e.g. Moore et al. 1991, Jenson 1991, Zhang and Montgomery 1994, and Wolock and McCabe 2000) also demonstrate that DEM grid size affects the results obtained for landscape attributes generated from DEMs. For example, coarser resolution DEMs give lower slope angles that those obtained from finer resolution DEMs.

Guth (2003) also suggests that geomorphic parameters can provide a quality check on DEMs. This has been hinted at several times in the literature. Moore et al. (1991) suggested that grid size should be based on the roughest terrain in a catchment to ensure that most variation is covered. McMaster (2002) advocates the determination of the threshold resolution beyond which a DEM is unsuitable for stream derivation. His work suggests this threshold is equal to the average slope length in a catchment.

Quinn et al. (1991, p. 63) asked ". . . distributed modelling of hillslope flows will require a grid scale much smaller that the scale of the hillslope, but how much smaller?" This question will be considered following the discussion of slopes in the next section.

3. DEMs AND SLOPES

Slope angles are not normally distributed. They are clustered around modal values that may be referred to as characteristic and threshold slopes (Young 1964). Characteristic slopes are those most commonly occurring in an area, and their inclination is controlled by the nature of the material (rock and regolith) on which they are formed and the processes that control their evolution. They are closely related to threshold slope angles, which are those where sudden changes of slopes processes take place. The existence of modal and threshold slope angles suggest that average slope values for an area have no explanatory value. These ideas are now demonstrated with reference to an area in NSW.

Near Picton, NSW, 14 slope profiles were constructed from a ground survey with slope angles measured over 5m intervals (Figure 1). The results show that there are four characteristic slope angles (Table 1, Figure 2) (Pain 1986). The lower mid slope is at the angle of long term stability, a value derived from the residual shear strength of the regolith in the area. Above 12^o landslides can occur, while below 12^o they can't; 12^o is thus an important threshold slope value in this area. 6-8^o is characteristic of both surface wash and soil creep, and therefore occurs in two slope units. Figure 2 shows the relationship between slope angle and processes. The controls on slope forms are bedrock geology, regolith and geomorphic processes. The data in Table 1 on which these conclusions are based were derived from ground surveys of slope angle and length of 14 profiles (Figure 1).

Table 1. Characteristic slope angles near Picton, NSW, Australia

Slope angles	Slope unit	Slope processes
28-30^o	Free face (cap rock)	Rock fall
22-24^o	Upper mid slope	landslides
10-12^o	Lower mid slope	Surface wash
6-8^o	Foot slope	Surface wash
6-8^o	Hill crest	Creep

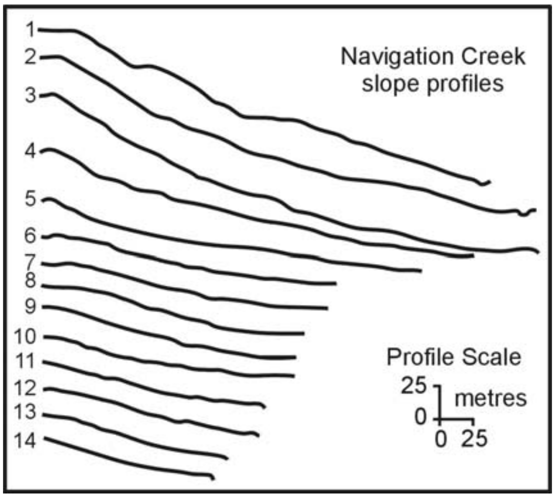

Figure 1. Fourteen measured slope profiles from different locations along a ridge at Picton, NSW, from Pain (1986).

Profile 1 (Figure 1) was selected to test the effects of DEM resolution. The profile was re-constructed by grouping ground measurements to simulate 25m, 50m and 100m DEMs. A profile along the same line derived from the 90m SRTM DEM is included for comparison.

Of the profiles shown in Figure 3, only the original survey and to a lesser degree the 25m "DEM" give any indication of the shape of the actual ground surface. The 50m and 100m DEMs have only a very broad resemblance to the ground surface, and any values derived from these latter DEMs would in no way reflect the original slope form. Moreover, they give no clue of the characteristic slope values in Table 1, so they in no way reflect the nature of the processes operating in this landscape. The SRTM 90m DEM over the same profile line similarly provides no information related to the real ground surface.

As noted above DEMs are frequently used to derive values such as slope angles (maximum, minimum and mean), slope lengths and slope aspect. However, the Picton data demonstrate that the accuracy of these derived values depends on the pixel resolution of the DEM from which they are derived (Figure 3).

The Picton data also demonstrate that average slope angles derived from the DEM have very little practical value. Moreover, even the 25m derived "DEM" does not adequately identify breaks-of-slope that are important in explanations of slope processes in the area. Thus the DEMs with a resolution of 25m or greater do not provide useful information about the way that landscape operates.

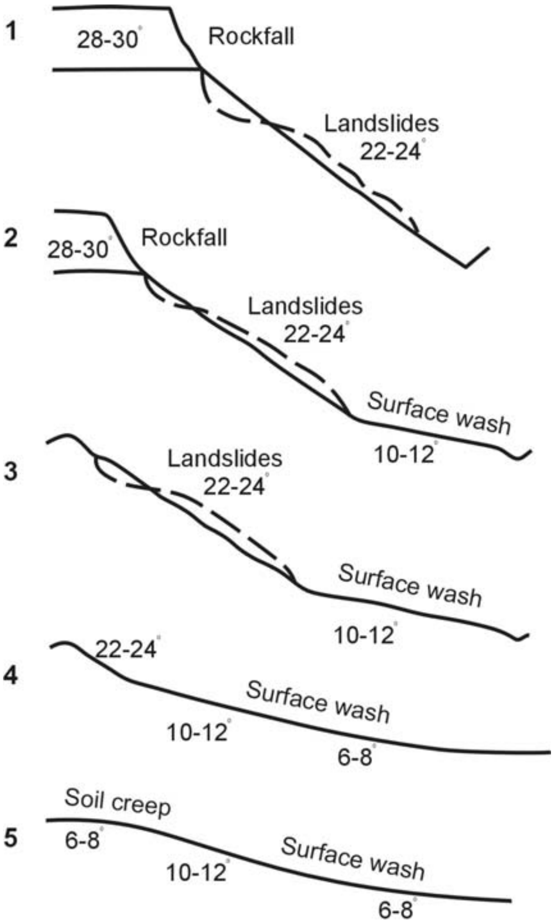

Figure 2. Diagrammatic representation of slope angles and geomorphic processes at Picton, NSW, from Pain (1986).

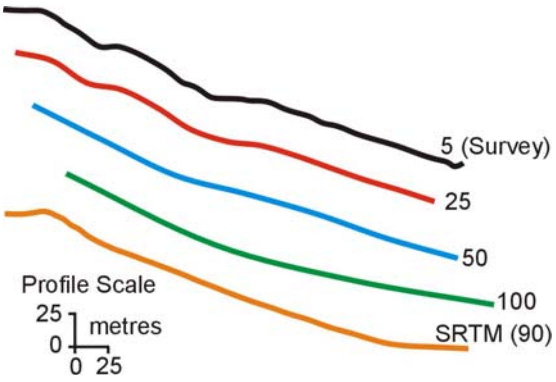

Figure 3. Slope profile 1 from Figure 1. The original profile (black) is constructed from a ground survey with slope angles measured over 5m intervals. The profiles below this were constructed by grouping ground measurements to simulate 25m, 50m and 100m DEMs. The lowermost profile is derived from the 90m SRTM DEM.

4. SCALE – WHY SIZE MATTERS

Quinn et al. (1991) asked how much smaller than the scale of hillslopes a DEM should be, while McMaster (2002) talked about threshold DEM resolution above which modelling would not be possible. The Picton hill slope data demonstrates that the scale of processes is much less than the hill slope length, and that a DEM resolution of about 5m is needed to bring out the modal and threshold slopes that characterise the way that landscape works. The presence of a threshold in DEM resolution also suggests that improvement of DEM accuracy is highly non-linear – processes can either be modelled or they can't. It also suggests that the scale of the processes can be regarded as indicating the threshold grid resolution.

It is thus clear that landscape scale plays a role in the use of DEMs. For example, it is likely that the lowland areas of the eastern Murray Basin could be represented adequately with a DEM of 100m resolution, whereas the upland areas of the eastern highlands that drain into the Murray Basin would need a much finer grid size. Multi-resolution tools are being developed to handle this landscape variation (e.g. Gallant and Dowling 2003, Sulebak and Hjelle 2003). It is well known that the spatial distribution of, say, soil moisture is highly variable and can change quickly with position in a landscape (e.g. Svetlitchnyi et al. 2003). Thus the appropriate scale for a particular landscape can only be determined by geomorphic analysis of landform shape and processes; in most cases this will mean ground survey.

5. CONCLUSION

Most DEMs have generalisations of the land surface built into them. If these generalisations are within the spatial range of the processes that are operating in the landscape of interest, there is no problem. However, if the generalisations are greater than the resolution of landscape processes, any results or indices derived from DEMs must be treated with caution. Thus slope angles derived from such DEMs are of limited value as descriptions of real landscapes, and useless in explanations of form and process unless the image data are at a resolution that equals or is better than the scale of slope and regolith processes. And although this paper does not consider other raster image data, the results imply that the same conclusions apply to them as well.

6. ACKNOWLEDGMENTS

I thank Jonathan Clarke, John Wilford, and two Anonymous referees for comments on the manuscript. This paper is published with the permission of the CEOs of Geoscience Australia and the Cooperative Research Centre for Landscape Environments and Mineral Exploration.

7. REFERENCES

Bende, U., Flugel, W-A. and Kern, T.J. (1995), Using GIS to delineate Chemical Hydrological Response Units (CHRUs) for hydrochemical modeling in a mesoscale catchment in Germany, *Effects of Scale on Interpretation and Management of Sediment and water Quality, IAHS Publication* 226: 133-139

Claessens, L., Heuvelink, G.B.M., Schoorl, J.M. and Veldkamp, A. (2005), DEM resolution effects on shallow landslide hazard and soil redistribution modelling, *Earth Surface Processes and Landforms* 30: 461-477.

Elvhage, C. and Lidmar-Bergstrom, K. (1987), Some working hypotheses on the geomorphology of Sweden in the light of a new relief map, *Geografiska Annaler* 69A: 343-358.

Fryer, J.G., Chandler, J.H. and Cooper, M.A.R. (1994) On the accuracy of heighting from aerial photographs and maps: implications to process modellers, *Earth Surface Processes and Landforms* 19: 577-583.

Gallant, J.C. and Dowling, T.I. (2003), A multi-resolution index of valley bottom flatness for mapping depositional areas, *Water Resources Research* 39: 1347-1360.

Gallant, J.C. and Hutchinson, M.F. (1996), Towards an understanding of landscape scale and structure, In *Proceedings, Third International Conference /Workshop on Integrating GIS and Environmental Modeling*, Santa Fe, NM, January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis: http://www.ncgia.ucsb.edu/ conf/SANTA_FE_CD-ROM/main.html.

Guth, P.L. (2003), Eigenvector analysis of digital elevation models in a GIS: geomorphometry and quality control, In Evans, I.S., Dikau, R., Tokunaga, E., Ohmori, H. and Hirano, M. (Editors), *Concepts and Modelling in Geomorphology: International Perspectives*, TERRAPUB, Tokyo: 199-220.

Harrington, H.J., Simpson, C.J. and Moore, R.F. (1982), Analysis of continental structures using a digital terrain model (DTM) of Australia, *BMR Journal of Australian Geology & Geophysics*, 7: 68-72.

Jenson, S.K. (1991) Applications of hydrological information automatically extracted from digital elevation models, *Hydrological Processes* 5: 31-44.

Johansson, M., (1999), Analysis of digital elevation data for palaeosurfaces in south-western Sweden, *Geomorphology*, 26: 279-295.

Jordan, G., Csillag, G., Szucs, A. and Qvarfort, U., (2003), Application of digital terrain modelling and GIS methods for the morphotectonic investigation of the Kali Basin, Hungary, *Zeitschrift fur Geomorphologie*, 47: 145-169.

Kuhlemann, J., Szekely, B., Frisch, W., Danisik, M., Dunkl, I., Molnare, G. and Timar, G., (2005), DEM analysis of mountainous relief in a crystalline basement block: Cenozoic relief generations in Corsica (France), *Zeitschrift fur Geomorphologie*, 49: 1-21.

Lidmar-Bergstrom, K., Elvhage, C. and Ringberg, B. (1991), Landforms in Skane, south Sweden, *Geografiska Annular* 73A: 61-91.

Lin, Z. and Oguchi, T. (2004), Drainage density, slope angle, and relative basin position in Japanese bare lands from high-resolution DEMs, *Geomorphology* 63: 159-173.

McMaster, K.J. (2002), Effects of digital elevation model resolution on derived stream network positions, *Water Resources Research* 38: 1042 (10.1029/2000WR000150).

Montgomery, D.R. (2001), Slope distributions, threshold hillslopes, and steady-state topography, *American Journal of Science* 301: 432-454.

Moore, I.D., Grayson, R.B. and Ladson, A.R. (1991) Digitl terrain modelling: a review of hydrological, geomorphological, and biological applications, *Hydrological Processes* 5: 3 30.

O'Neill, M.P. and Mark, D.M. (1987), On the frequency distribution of land slope, *Earth Surface Processes and Landforms* 12: 127-136.

Pain, C.F. (1986), Scarp retreat and slope development near Picton, New South Wales, Australia, *Catena* 13: 227-239.

Park, S.J. and van de Giesen, N. (2004), Soil-landscape delineation to define spatial sampling domains for hillslope hydrology, *Journal of Hydrology* 295: 28-46.

Pickup, G. and Marks, A. (2000), Identifying large-scale erosion and deposition processes from airborne gamma radiometrics and digital elevation models in a weathered landscape, *Earth Surface Processes and Landforms* 25: 535-557.

Quinn, P., Beven, K., Chevallier, P. and Planchon, O. (1991), The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models, *Hydrological Processes* 5: 59-79.

Roberts, D.W., Dowling, T.I. and Walker, J. (1997), FLAG: a fuzzy landscape analysis GIS method for dryland salinity assessment, *CSIRO Land and Water Technical Report* 8/97.

Schoorl, J. M., Sonneveld, M. P. W. and Veldkamp, A. (2000), Three-dimensional landscape process modelling: the effect of DEM resolution, *Earth Surface Processes and Landforms* 25: 1025-1035.

Smith, M.J. and Clark, C.D. (2005), Methods for the visualization of digital elevation models for landform mapping, *Earth Surface Processes and Landforms* 30: 885-900.

Sulebak, J.R. and Hjelle, Ø. (2003), Multiresolution spline models and their applications in geomorphology, In Evans, I.S., Dikau, R., Tokunaga, E., Ohmori, H. and Hirano, M. (Editors), *Concepts and Modelling in Geomorphology: International Perspectives*, TERRAPUB, Tokyo: 221-237.

Summerell, G.K., Dowling, T.I. Wild, J.A. and Beale, G. (2004), FLAG UPNESS and its application for mapping seasonally we to waterlogged soils, *Australian Journal of Soil Research* 42: 155-162.

Svetlitchnyi, A.A., Plotnitskiy, S.V. and Stepovaya, O.Y. (2003), Spatial distribution of soil moisture content within catchments and its modelling on the basis of topographic data, Journal of Hydrology 277: 50-60.

Thelin, G.P. and Pike, R.J. (1991), Landforms of the conterminous United States - a digital shaded- relief portrayal, *U.S. Geological Survey Miscellaneous Investigations Map* 2206, 1:3,500,000 scale: 16pp.

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

Wilson, J.P. and Gallant, J.C. (Editors) (2000a), *Terrain Analysis: Principles and Applications*, John Wiley and Sons, 479pp.

Wilson, J.P. and Gallant, J.C. (2000b), Digital terrain analysis, In Wilson, J.P. and Gallant, J.C. (Editors) *Terrain Analysis: Principles and Applications*, John Wiley and Sons: 1-27.

Wolock, D.M. and McCabe, G.J. (2000) Differences in topographic characteristics computed from 100- and 1000-m resolution digital elevation model data, *Hydrological Processes* 14: 987-1002.

Young, A. (1964), Slope profile analysis, *Zeitschrift fur Geomorphologie, Supplement Band* 5: 17-27.

Zhang, W. and Montgomery, D.R. (1994) Digital elevation model grid size, landscape representation, and hydrologic simulations, *Water Resources Research* 30: 1019-1028.