Automated Slope Classification Using Digital Elevation Models

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Abstract: Three major natural resource management agendas in New South Wales – native vegetation, water and dryland salinity – have increased the demand for natural resource information. An important factor for assessing native vegetation management proposals and in predicting dryland salinity hazard is land surface slope. This information is not currently comprehensively available. Slope class maps produced by Air Photo Interpretation (API) and digitisation are labour intensive and time consuming, whereas automated methods using Digital Elevation Models (DEMs) have not so far produced results acceptable to natural resource managers. Accuracy, appearance and representation of steepest and flattest classes are key problems for DEM based methods. This paper describes a method developed to overcome the problems with automated slope mapping. The main improvements over simpler approaches are the calculation of slope along flow paths covering several DEM cells in low and high parts of the landscape, and in the aggregation of fragments into suitably sized regions using a cost-distance accumulation method. Compared with the raw classified slope, the result has both better agreement with the API-generated map and better appearance. Field testing of areas of differences between the two methods indicated that both methods equally misrepresent slope. The method is under consideration for production of slope class maps on a state-wide basis. However, these maps may need to be refined and adjusted in crucial areas using API.

Keywords: Slope mapping; Digital elevation models; Terrain analysis

1. INTRODUCTION

1.1. Background

Slope is a fundamental property of the landscape that drives movement of water and soil downwards and across the surface. Slope is a constraint on the use of land, as steep slopes are liable to be unstable and hence unsuitable for agriculture or urban development. Knowledge of slope steepness is an important component of land suitability analysis.

1.2. Slope Mapping by API

Slope mapping has traditionally been carried out using API. The mapping of slope is often included as part of a comprehensive landform mapping activity [K. Emery, pers. comm.]. The product of such mapping is usually a division of the landscape into polygons each with a particular slope class, terrain classification, and other attributes). Within the NSW Department of Land and Water Conservation (DLWC), slope mapping uses the slope classes shown in Table 1.

Table 1. Slope classes used for slope mapping within DLWC

Class	Slope range
1	0 – 1%
2	1 – 2%
3	2 – 5%
4	5 – 10%
5	10 – 20%
6	20 – 33%
7	33 – 50%

Figure 1 shows a slope map derived using API. The area shown is a section of the Afterlee 1:25 000 map sheet in the Richmond River catchment in northern NSW. Particular features to note in this map are:

- Connected polygons following main topographic features such as valley floors
- A minimum size of mapped features of about 1 ha

Slope maps produced by API require 2-4 weeks work depending on the complexity of the landscape and the skill of the mapper [K. Emery, pers. comm]. Skilled air photo interpreters are scarce nowadays, and the production of slope maps for the eastern portion of NSW for which 1:25 000 scale mapping exists would take 2-5 person years. More rapid automated methods are therefore of great interest to natural resource management agencies.

1.3. Slope Maps from DEMs

With the advent of readily available digital elevation models (DEMs) and terrain analysis packages [Wilson and Gallant, 2000], it would seem practical and efficient to derive slope maps automatically from DEMs rather than using manual methods. The calculation of slope from a DEM is a relatively trivial operation [Gallant and Wilson, 2000], as is the classification of derived slope into classes. Unfortunately, this simple approach produces a poor quality product with very different characteristics to a traditional API-derived slope map. Figure 2 shows the same area as Figure 1 mapped using this straightforward method from DEMs. The most obvious problems are:

- Fragmentation, where there is a prevalence of single cells or small clusters of cells in a single class as opposed to organised regions;
- Under-representation of low slope classes, particularly narrow valley floors and ridges

1.4. Objectives

The objective of the work reported here was to explore the feasibility of deriving slope class maps of acceptable quality from DEMs. The derived maps should be similar to API-derived maps with a similar level of aggregation and connectedness. The main challenges were to overcome the disconnected nature of the simple DEM-derived map, and to overcome the tendency of DEM-derived slope to overestimate slope in valley bottoms and ridge top areas. The API map was used as a reference while acknowledging that the DEM-derived map would not be expected to exactly reproduce the features and classification in the API map.

2. METHODS

The methods described were applied on 25 m resolution DEM derived from 1:25 000 scale contours and streamlines using the ANUDEM program [LPI, 2001; Hutchinson, 2001]. The DEM covers a 14 x 24 km area (555 x 979 grid cells). The methods were mostly applied using the Arc/Info GIS [ESRI, 2001].

Preliminary evaluation of the raw slope class map resulting from classifying the slope showed:

- Slopes are over-estimated where API-mapped slope is in class 1, 2 or 3 (<5%).
- Slopes are under-estimated where API-mapped slope is in class 5-7 (>20%)
- The area occupied by class 4 (10-20%) is over-estimated by a factor of 2
- Some of the disagreement between DEM- and API-derived maps is due to spatial misalignment , where obvious features such as narrow valleys do not exactly coincide, resulting in apparent over- and under-estimation of slope.

No attempt was made to deal with spatial misalignment, but a number of approaches were explored in developing a method that alleviated the problems with the slope class distribution.

2.1. Unsuccessful Approaches

Simple approaches such as smoothing slopes and aggregating classes were evaluated. However, these did not produce satisfactory result. Smoothing slopes prior to classifying reduced fragmentation, but exacerbated problems with low slopes and increased over-abundance of class 4 (Table 2). Aggregating classes to a majority vote in a 2 cell radius also reduced fragmentation but reduced the correspondence with API results.

2.2. Successful Approach

The most successful approach uses a combination of three algorithms. The first directly deals with the problem of low slopes, and the second and third deal with production of connected regions of a defined minimum size.

2.2.1 Calculating slope along flow lines

Narrow regions of low slope on valley bottoms and ridge tops are poorly defined by simple slope calculations for two reasons. The first is that DEMs derived from contours cannot easily capture the narrow flat valley floors and flat ridge tops identified in the manual slope mapping, partly due to the difficulty of mapping these features by contours and partly due to the resolution of the DEM. The second is that estimates of slope from DEMs are calculated over a window of 3 cells, so the estimated slopes of valley bottoms and ridge tops can be increased by the slope of the adjacent hill slopes. The second

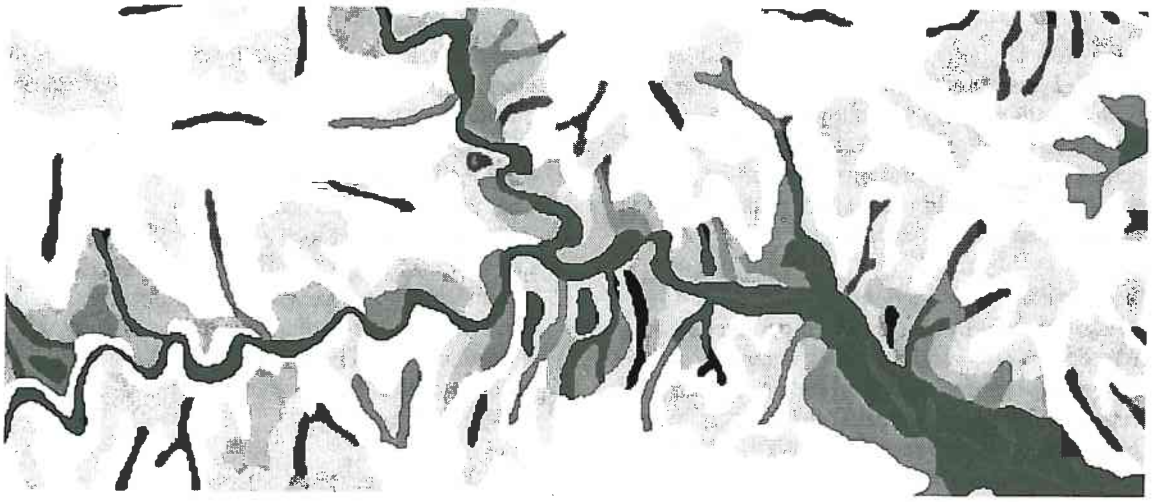

Figure 1. Slope map produced by manual air photo interpretation.

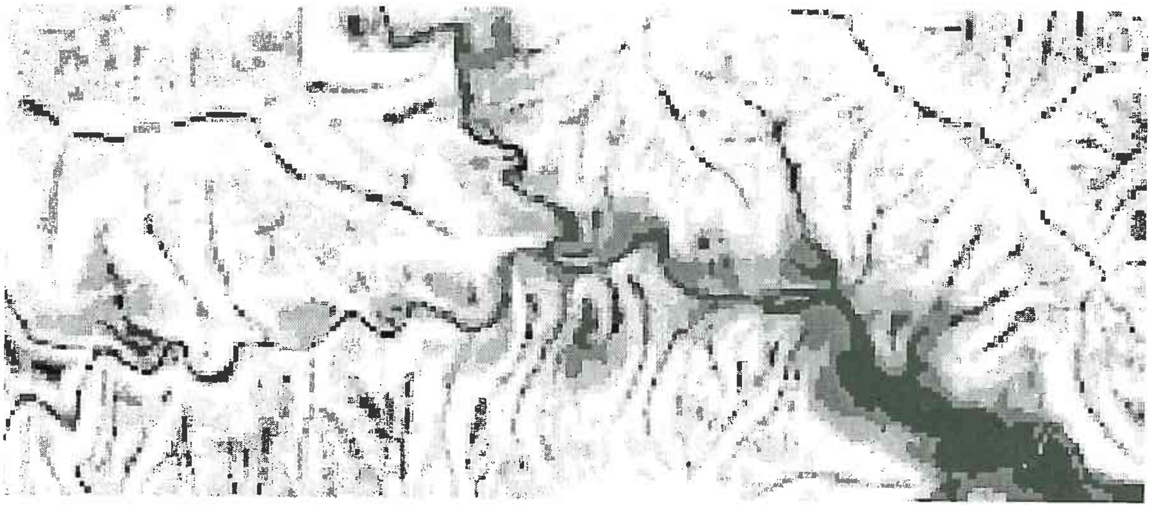

Figure 2. Slope map produced by classifying slope calculated from DEM.

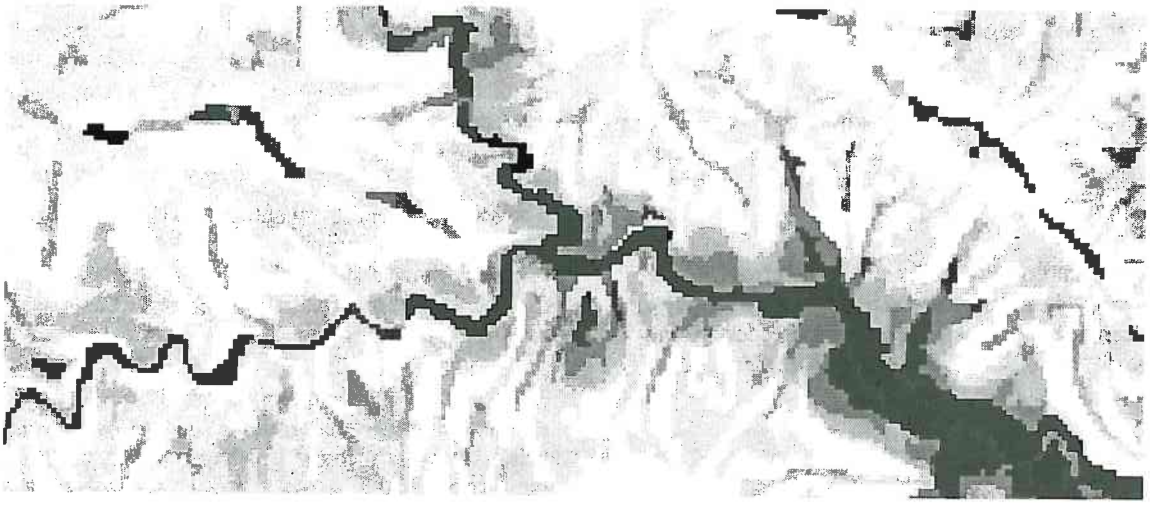

Figure 3. Final slope map from DEM using flow path slope, cost distance region growing and cleaning.

problem can be largely overcome by calculating slope along the direction of steepest slope rather than in all directions; in valleys the downslope direction is used and on ridges the upslope direction is used. The first problem can be partly overcome by computing slope along the flowpath over more than one cell distance.

This algorithm was implemented using a C++ program (flowslope) that takes as parameters the DEM, downwards and upwards steepest slope paths, a maximum distance and a maximum elevation difference. Steepest slope paths were defined using ArcInfo's FLOWDIRECTION command, applied to the normal DEM for the downward paths and to an inverted DEM (the DEM subtracted from a large number) for the upward paths. The maximum distance was set to 100 m (4 cells) and the maximum elevation difference 3 m (1/3 contour interval). The three slope maps were merged by using a ranking of cells within a 150 m radius window by the ElevResidGrid program [percentile output; Gallant and Wilson, 2000] with values less than 0.2 defining valleys and greater than 0.8 defining ridges.

Application of this algorithm to derive slope, followed by classification as in the simplest approach, substantially improved the representation of low slopes and the overall slope class distribution, but did not improve the fragmentation of the result.

2.2.2 Region growth with cost distances

The fragmentation was addressed by a method to directly produce larger homogeneous units based on finding areas with similar slope.

This method begins by finding cells that are within the core region of a slope class, that is, within the middle 50% of the range of slopes for each class. Core values for class 1 were values less than 1.5% and for class 7 were values greater than 55%. Cells within these core value ranges are called seed cells.

Complementing the seed cells is an error surface for each class, which measures the difference between the slope at a point and the core slope range for that class. The error value for slope s and class i is:

$$error = \begin{cases} (\log s - \log s_{\min})^2 & s < s_{\min} \\ 0 & s_{\min} \le s \le s_{\max} \\ (\log s_{\max} - \log s)^2 & s > s_{\max} \end{cases} \qquad (1)$$

The values $\log s_{min}$ and $\log s_{max}$ are set 0.1 inside the boundaries of the slope class. This error is zero for core values, small for values within the class but increases rapidly as the value departs outside the class boundary.

Regions are grown outwards from the seed cells with the error value accumulating the error value for each cell added to the region. This is achieved using ArcInfo's COSTDISTANCE function. The accumulated cost increases in proportion to the error in including the cell in the region for a particular class. The region growing is constrained to stop when the cost exceeds 2.0 to reduce computation time.

After the cost distance calculations are complete, each cell has an error value for each of the 7 slope classes. The region-growing approach ensures that the lowest errors occur in connected regions. Using the lowest cost value to assign a class for each cell produces a map with reasonably good aggregation characteristics, but still includes a degree of fragmentation that is resolved with the final algorithm

2.2.3 Joining and cleaning

The final step is to deal with any remaining regions that are smaller than the defined minimum size (1 ha, or 16 cells at 25 m resolution). This algorithm gives preference to the classes that tend to be under-represented in the class maps derived to this point.

The first step in this part of the process is to identify any regions of a class 1 and 2 that contain fewer than 16 cells. Any such regions that are adjacent are then combined into a single region, and the slope class for the combined region is determined from the average of the slopes within the region. This process is then repeated for classes 1 through 3 and then for classes 1 through 4. The process is designed to maximise the chances for a valley region with low slope but disconnected classes to be aggregated into a single region with low slope.

The same process is repeated for classes 6 and 7, then classes 5 through 7. Finally, the joining process is applied without restriction on the classes, so that small adjacent regions of any class can be combined.

This process still leaves some isolated small regions. These are identified, then progressively filled from their edges by the dominant class in the surrounding area, using the Arc/Info FOCALMAJORITY function. Where there is a tie for majority, the cells are filled alternately from the left and right until no more undefined cells remain.

3. ASSESSMENT

Figure 3 shows the same area as before mapped using the automated method as described.

3.1. Visual Appearance

Apart from the blocky appearance induced by the grid structure of the DEM, Figure 3 is reasonably similar to the API produced map of Figure 1. The smallest features are of similar size, and some of the same shapes are captured. Some features are missed, such as the channel feature within the narrow floodplain, while in other areas the DEM-based map is more detailed than the API-based map. There are many disagreements between the two maps, even where the same shaped features are identified.

3.2. Quantitative Comparison

Table 2 shows the frequency distribution of classes obtained from the API, simple DEM slope and the final product, as well as percentage agreement between the DEM-based results and the API map. While the agreement remained disappointingly low overall (less than 50% of cells were classified in the same class as the API map), both the distribution and percent agreements are significantly improved by the method developed here.

Table 2. Frequency distribution of classes from manual (API) mapping, classification of raw slope, and the final slope map; and percent agreement between API and DEM-derived slopes.

Slope Class	% of cells (% agreement with API)		
	API	Raw slope	Final slope
1	11	4 (34)	6 (47)
2	8	7 (22)	8 (30)
3	13	12 (29)	19 (46)
4	15	29 (58)	17 (42)
5	26	28 (50)	24 (49)
6	19	15 (43)	18 (52)
7	8	5 (36)	8 (53)

3.3. Field Testing

Ground slope observations of the Afterlee 1:25 000 map sheet area were conducted in order to clarify the discrepancies between the two slope class maps. Areas where there were obvious differences in the maps were marked to be checked in the field. It must be noted, however, that most of the samples were taken within 100 metres of a road, so there may be some bias in the results.

A total of 130 slope samples were taken in the area and then compared to the results of the DEM and API produced slope maps (Table 2). Overall the API produced slope map was only slightly higher in the number of correct readings. The DEM slope map achieved better results in classes 2, 3 and 6, whereas the API slope map had better results in classes 1, 5 and 7. The API slope map tended to underestimate slope across all classes, whereas the DEM tended to overestimate classes 1 to 3 and underestimate classes 4 to 7.

The DEM produced slope map was better at representing ridgelines, drainage lines and upper slopes than the API slope map. It was more accurate in picking up detail in the grading of slopes from floodplain to foot slopes and foot slopes to hillslopes. The DEM slope map also tended to be more accurate in some dissected floodplains whereas the API tended to generalise floodplains in slope class 1.

In other areas of the landscape, however, such as minor spurs and knobs or small confined floodplains, the DEM tended to average everything into one unit, where there should have been a range of classes. This was attributed to a lack of contour information in the DEM. The DEM slope map had problems in the lower slopes, as it tended to over-accentuate the foot slopes connected to the floodplain, causing a higher slope to be recorded on the floodplain. Again this can be attributed to the nature of the contour data and the interpolation.

The API slope map was usually within one slope class when it was incorrect, however the DEM map could be out by as much as three classes.

4. CONCLUSIONS AND FURTHER WORK

While the automated slope map produced from the DEM has some errors, the errors on the whole are no worse than those in the traditional API method. The DEM-based method is quick, repeatable and explicit, whereas the API method of slope class mapping is subjective and very time consuming. The DEM produced slope map is easily readable, the slope classes look neat and the sequences appear generally accurate, which satisfies the aim of the method.

The automated processing of the Afterlee map sheet requires approximately 15 hours on a Sun Sparc10 workstation.

The recent development of a method for mapping low relief areas from DEMs [Gallant and Dowling, in prep] may further improve the reliability of DEM-derived slope maps.

Table 3. Summary of results of slope reading compared to DEM and API slope class maps. (* Total numbers are not the same where the observed was between two slope classes (eg. 2, 5 or 10%) and the slope maps showed either of the classes).

	Correct readings		Number of classes above observed			Number of classes below observed			Total
	%	No.	1	2	3	1	2	3	
DEM (total)	68	89	13	5	-	17	4	2	130
Class 1	19	3	9	4	-	-	-	-	16*
Class 2	89	24	2	1	-	-	-	-	27*
Class 3	100	28	-	-	-	-	-	-	28*
Class 4	64	14	2	-	-	5	-	1	22*
Class 5	64	16	-	-	-	7	2	-	25
Class 6	30	3	-	-	-	4	2	1	10
Class 7	50	1	-	-	-	1	-	-	2
API (total)	72	93	9	-	-	25	3	-	130
Class 1	100	17	-	-	-	-	-	-	17*
Class 2	83	24	-	-	-	5	-	-	29*
Class 3	63	15	2	-	-	5	2	-	24*
Class 4	65	15	5	-	-	2	1	-	23*
Class 5	72	18	2	-	-	5	-	-	25
Class 6	20	2	-	-	-	8	-	-	10
Class 7	100	2	-	-	-	-	-	-	2

5. ACKNOWLEDGEMENTS

The work described in this report was partly funded by NSW Department of Land and Water Conservation.

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