An Evaluation of Digital Elevation Models for Upgrading New Zealand Land Resource Inventory Slope Data.

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Abstract

Slope is a key environmental parameter which influences land use and erosion hazard. Digital elevation models (DEMs) are often used to map important topographic parameters such as slope. However, the quality of such maps depends on the quality of the DEM's representation of the earth's surface. In many cases errors in this representation are neither measured nor estimated. In this paper a real-time differential GPS is used to acquire ground truth data. This ground truth is compared with DEMs generated from contours. This analysis shows that three commonly used contour-based interpolation procedures all produce good quality DEMs.

When considering the replacement of more traditional slope maps based on field mapping or air photo and contour interpretation with DEM-derived slope maps, it is important to establish that DEM-derived slope maps do represent an improvement on existing approaches. This paper compares field mapped and DEM-derived slope maps with slopes calculated from GPS elevation data. It shows that DEMs can provide both improved spatial resolution and increased accuracy in slope maps.

1. Introduction

The New Zealand Land Resource Inventory (NZLRI) has been the primary source of land resource information for New Zealand since the early 1970s. The data in the NZLRI came from field mapping. Areas of relatively homogeneous land (polygons) were defined using aerial photographic interpretation, topographic maps and field survey. For each polygon the following attributes were recorded: rock type, soil, slope, vegetation, erosion and land use capability classification. Although the NZLRI has been stored in digital form in a Geographic Information System (GIS) since 1973, the database structure has retained its original "paper-map" format, as a single geographic layer with multiple attributes. Restructuring the database to better utilise current GIS analytical capability has been hindered by the difficulty of separating key attributes from the existing single layer, and/or the cost of remapping individual attributes. Landcare Research has identified the potential for technologies such as remote sensing (Dymond, 1992b, 1995a; Wilde, 1996) and digital elevation models (Dymond, 1992a, 1994, 1995b) to be used in operational mapping or updating of the database but they have not yet been utilised widely.

Slopes derived from digital elevation models (DEM) could be used to upgrade the slope attribute currently stored in the NZLRI. However, most DEMs are interpolated from the most commonly available source of topographic data - digital contours which in turn have been generated photogrammetrically from aerial photographs. In many cases there is no quantitative assessment of DEM accuracy, and error propagation to secondary parameters such as slope and aspect is not addressed (Fryer, 1994).

In this paper we investigate the development of a raster layer of slope data to replace the classified attribute recorded in the original NZLRI polygons. In particular, we review measures for determining DEM accuracy, and investigate the magnitude of errors in slope as calculated from DEMs. We also analyse the relative merits of data collected using field survey methods and DEM-based slope maps.

2. Measuring Accuracy

2.1 DEM

There are many potential sources of errors in DEMs. Contours are the most common form of topographic data from which DEMs are derived. Contours are derived using photogrammetric methods. For 8x10 inch photography gathered at 1:50000 scale these methods can lead to heighting errors of ± 0.6 m for spot heights, and ± 0.7 m for contours just from random errors in the photogrammetric process (Fryer, 1994). This could lead to contour displacements of 140 m on a flood plain with 0.25° (0.5%) slope. Most mapping organizations only guarantee that contour lines are correct horizontally to within half the horizontal interval between the contour lines 90% of the time (Fryer, 1994).

To determine DEM accuracy, we need some independent knowledge of the topography to determine the difference between the digital surface and the real elevations of the same locations on the ground. This requires both a suitable sample of ground truth points, and suitable statistics from which to derive error terms (Monckton, 1994). Most commonly such ground truth points are taken from the same topographic database as the contours, in the form of local spot heights recorded at trig stations and local peaks. However, trigs and spot heights do not provide a good sample of the landscape since they over-represent peaks, under-represent low areas, and may be non-randomly distributed (ie., biased towards hilly areas). Acquisition of ground truth points should preferably be derived by independent survey, either photogrammetric (eg., Fryer, 1994), or traditional field survey (eg., Monckton, 1994). A new method of obtaining ground truth points is by using Global Positioning Systems (GPS) which estimates position (easting, northing and elevation) from satellites.

The root mean square error (*RMSE*) between DEM and ground truth elevations can be used to measure DEM accuracy :

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \quad (1)$$

where n = number of points

d_i = $z_{ground.i}$ - $z_{dtm.i}$

$z_{ground.i}$ = ground elevation recorded at point i

$z_{dtm.i}$ = DEM elevation at point i

Alternatively Li (1988) advocates the use of the standard error (*S*) and mean error ($\bar{d}$)

$$S = \sqrt{\frac{\sum_{i=1}^{n} (d_i - \bar{d})^2}{n}} \text{ where } \bar{d} = \frac{\sum_{i=1}^{n} d_i}{n} \quad (2)$$

RMSE is the more widely used statistic but assumes a zero mean error, and therefore no systematic bias in the DEM (Li, 1988). Both Li (1988) and Monckton (1994) suggest that this assumption is not justified.

2.2 Slope

As with DEM elevation, slopes calculated from a DEM surface are subject to several sources of error. Skidmore (1989) provides an analysis of the algorithmic accuracy of six methods for calculating slope and aspect. However, algorithmic accuracy is only one source of error in calculated slope. An important issue that does not appear to have been addressed is calculating how elevation errors propagate through slope calculations (Fryer, 1994). This may be because slope maps, while easy to produce, can be difficult to reconcile with field measurements of slope (Dymond, 1994). This is because field measurements of slope are usually "integrated" over "slope length" by an observer, whereas DEM slope is generated for a fixed slope length which is related to the sampling interval (ie., the DEM resolution). Some degree of integration over slope length is vital to avoid "noise" from micro-topographic variations of slope which could only be mapped at very large scales. However, there are no recognised standards for defining slope length. As a result, analysis of slope errors presents significant problems because the accuracy of any ground truth slope data is unknown. Ground truth data have been derived through manual interpretation of contour data (Skidmore, 1989). Such data may be useful for testing algorithmic accuracy, but seem a questionable source of ground truth. Hammer (1995), and Dymond (1994) used detailed ground survey to locate grid points for each DEM cell centre and/or manually measured slope by clinometer to gather independent ground truth data.

Calculated slope data can be compared to measured ground truth slope data in a number of ways. Dymond (1994) used a graphic interpretation with associated trend or correlation statistics. Skidmore (1989) used Kendall's tau measure of association and Spearman's rank correlation coefficient to test for a significant positive correlation between true and calculated slopes. Hammer *et al.* (1995) classified slopes into 5° classes and reported the percentage of cells in the matrix correctly classified, and correct to within one class.

Methods

3.1 GPS-based Ground Truth Data Collection

A Trimble GPS Pathfinder Pro XL system was used to collect ground truth location/elevation data. The system utilised a radio-link to a GPS base station service to deliver real-time differential positions with nominal sub-metre accuracy given a precision dilution of position (PDOP) of 4 and satellite elevation mask (SEM) of 15 degrees. Coordinate data from the GPS were recorded using the same coordinate system as the digital contours and topographic base data (the New Zealand Map Grid), allowing "way points" to be aligned as closely as possible with the 25 m grid of the DEMs interpolated from contours, given limitations imposed by trees and rock bluffs at a small percentage of sites.

Data was collected for two areas in the vicinity of Mt Vernon, on the Port Hills south of Christchurch (Fig 1). Area one included 400 points on a 25 m grid (500 m^2) for the north facing slopes below Mt Vernon, and area two 100 points in a 250 m^2 area over a rolling ridge crest north east of Mt Vernon. For the majority of the data collection PDOP values remained at 4 or better. However, in the deepest parts of the gully in the larger of the two areas, the steep terrain and limited horizon resulted in fewer satellite links, higher PDOPs, and lower positional accuracy. Data from the GPS were converted to a "ground truth DEM" simply by allocating each grid square the elevation value recorded at its centre.

3.2 NZLRI Slope Mapping

The study area on the Port Hills was mapped during the 1st edition phase of NZLRI mapping (Hunter, 1976), but has not been remapped to 2nd edition standards. To use only 1st edition data for an accuracy analysis with DEM slope data would not be a fair reflection on the whole NZLRI database, which contains, particularly in the North Island, substantial areas of 2nd edition mapping. To make an approximate assessment of the accuracy of slope mapping in the 2nd edition NZLRI, two scientists who were involved in both 1st and 2nd edition NZLRI mapping carried out a blind resurvey of the study area and surrounds (i.e., without exact knowledge of the location of the GPS survey) by interpreting aerial photographs and topographic contour data. Their slope maps (now referred to as 2nd edition NZLRI) were digitized, converted to 25 m raster format and compared with the ground truth slope maps. In addition, a detailed soil survey of the Port Hills (Trangmar, 1991) that included a classified slope attribute was converted to a 25 m resolution grid for comparison.

3.3 DEM Generation

Three 25 metre resolution DEMs were generated from three commonly used interpolators using Land Information New Zealand (LINZ) 20 m contours from the 1:50,000 topographic database. Two of the interpolators were from within ARC/INFO. They are referred to here as the ARCTIN and TOPOGRID methods. The ARCTIN method

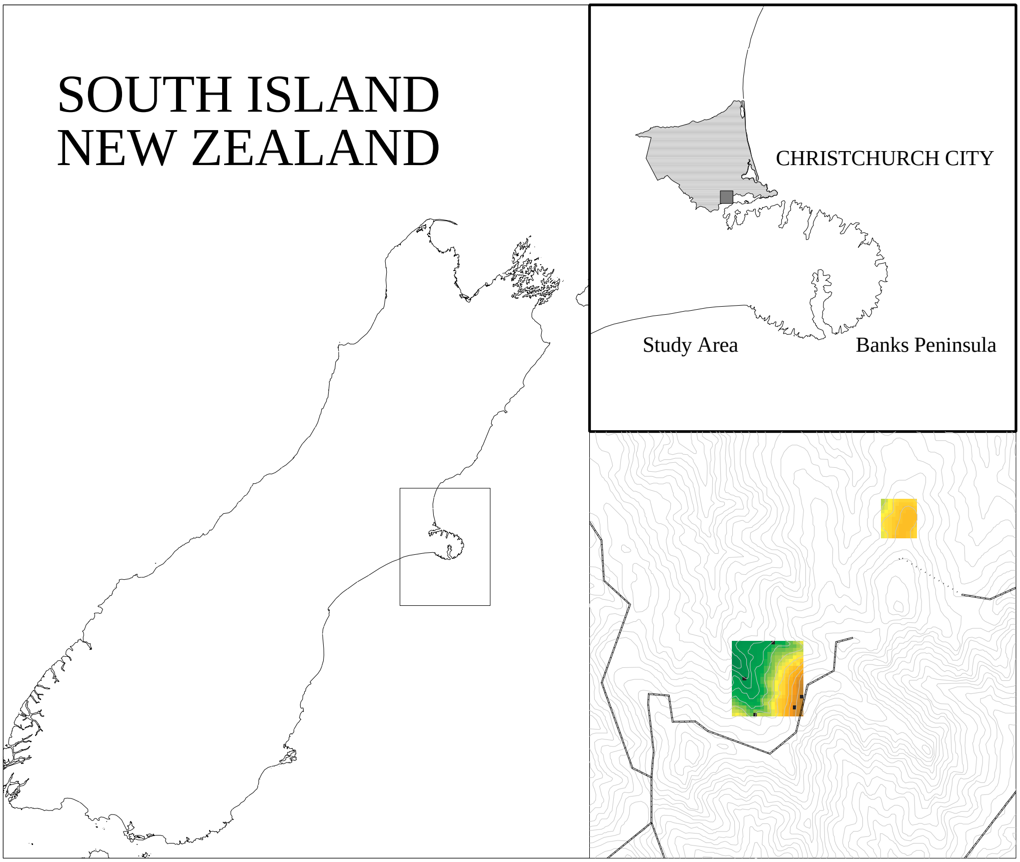

Figure 1: *location map*

uses CREATETIN to make an irregular triangular network (TIN), then uses the TINLATTICE command with the linear option to convert the TIN to a DEM. The TOPOGRID method is the ARC/INFO implementation of ANUDEM (Hutchinson, 1989). An interpolator developed in-house by Landcare Research, referred to here as the GILTRAP method (Giltrap, in prep.), was also used.

3.4 Slope Generation

Slope was calculated using the ARC/INFO GRID function SLOPE, which utilises a 3 x 3 window to calculate slope using the third-order finite difference method originally proposed by Horn (1981).

$$slope = \arctan\sqrt{\left[\left(\frac{\sigma z}{\sigma x}\right)^2 + \left(\frac{\sigma z}{\sigma y}\right)^2\right]} \quad (3)$$

where $\frac{\sigma z}{\sigma x} = \frac{((a+2d+g)-(c+2f+i))}{8 \times cell - resolution}$

and $\frac{\sigma z}{\sigma y} = \frac{((a+2b+c)-(g+2h+i))}{8 \times cell - resolution}$

with 3 x 3 cell notation as follows

a	b	c
d	e	f
g	h	i

Slope maps were generated from the DEM created by the ARCTIN method ("ARCTIN interpolated slope map") and from the DEM created from the GPS data ("GPS ground truth slope map").

	ARCTIN	GILTRAP	TOPOGRID
RMSE	5.77	7.76	7.94
mean error (_)	0.29	5.00	-4.06
S	5.76	5.85	6.80

Table 1: *Comparison of accuracy statistics for DEM surfaces generated from 20 m digital contours using different interpolation algorithms. These figures compare favourably with published USGS DEM standards for Level 1 DEMs for which "a vertical RMSE of 7 meters or less is the desired accuracy standard", and "an RMSE of 15 meters is the maximum permitted" USGS (1996).*

4. Results

4.1 Accuracy of Elevation Estimates

Table 1 presents the *RMSE*, _ and *S* statistics from a comparison of DEMs created by the ARCTIN, TOPOGRID, and GILTRAP methods with the ground truth DEM. The table shows that the ARCTIN-based DEM had the lowest *RMSE*, with the GILTRAP and TOPOGRID DEMs having similar *RMSE* statistics. The ARCTIN DEM also had the lowest _ and standard error statistic. The GILTRAP method generally over-estimates elevation by 5 metres, while the TOPOGRID method under-estimates elevation by a similar amount. The standard error statistic suggests that the ARCTIN and GILTRAP methods perform slightly better than the TOPOGRID method when interpolating from contours alone.

For all three methods these figures compare favourably with those quoted as standard for USGS DEMs (USGS, 1996) despite the use of trig stations and spot heights as ground truth points in USGS analyses. For example, level 1 USGS 7.5 minute DEMs must have an *RMSE* of less than 15 metres, and preferably less than 7 metres.

4.2 Accuracy of Slope Estimates

The classification matrix (table 2) illustrates the match between the ARCTIN interpolated slope map and the GPS ground truth slope map when both maps were classified into 5° classes. Some 36% of cells have the correct slope class assigned (±2.5°), while 83% of all cells are correct to within one slope class (±7.5°). This compares favourably with results reports from an analysis using a 30 m USGS DEM (Hammer, 1995).

In any calculation used for estimating slope from a DEM surface, elevation errors in the DEM surface are propagated through to the slope map. In this study maximum

ARCTIN Interpolated Slope Class	GPS Ground Truth Slope Class							
Class	1	2	3	4	5	6	7	Total Cells
0	12	4	1					17
1	4	6	1					11
2	1	9	5	1				16
3	3	23	34	22	8	2	2	94
4		13	35	69	61	6	2	186
5	2	3	10	40	65	12	5	137
6			2	12	26	10		50
7			2	3	3	1	2	11
8					2		1	3
Total cells	22	58	90	147	165	31	12	525
%correct	18.2	15.5	37.8	46.9	39.4	32.3	16.7	36.8
% within one	77.3	65.5	82.2	89.1	92.1	74.2	25.0	83.4

Table 2: *Comparison of slopes derived from GPS ground truth survey and ARCTIN-based DTM. Of the 525 cells 37% are correctly classified (± 2.5°) and 83% are correct within one slope class (± 7.5°).*

elevation errors at any cell were found to be approximately ±20 metres. Within a 3 x 3 cell window this equated to a maximum possible error in height differential (see equation 3) of 40 metres over a distance of 50 metres (ie., twice the cell resolution) which results in a worst-case slope error of » 38°. Even at low error levels (±3 metres), the propagated error in slope is close to 5°, or within one 5° class of the true slope. The mean elevation error within the study area was ±5 metres which would result in a worst-case slope error of » 10°. The actual maximum error between the GPS ground truth slope map and the ARCTIN interpolated slope map was found to be » 22°, but errors of this magnitude are confined to a gully bottom where the GPS ground truth DEM is least reliable because of higher PDOP values. Elsewhere in the study area slope error rarely exceeded 10°, and was usually less than 5°.

4.3 Comparison with the NZLRI slope map

As the aim of this study is to determine whether a DEM derived slope map can improve on the NZLRI slope data, we have compared the NZLRI with the GPS ground truth slope map. All of the Mt Vernon study area falls within one 1st edition NZLRI polygon which is recorded as having F class slopes. This class includes slopes of between 26° and 35°. By reclassifying the GPS ground truth slope map using the NZLRI classification scheme, 'A' through 'G' (Water & Soil Division, 1969), only 7% of cells are correctly classified, while 35% are classified within one class of correct (ie., E or F slopes - between 21° and 35°).

The study area overlaps six polygons in the 2nd edition NZLRI which have slope classifications ranging from C (8-15°) to F (26 - 35°). When compared with the GPS ground slope map, 31% of cells are correctly classified, and 76% are correct within one class. Agreement between 2nd edition NZLRI and the ARCTIN interpolated slope maps shows good agreement (37% correct and 76% within one class) over the 3 km^2 area surrounding the GPS survey areas (Fig. 1).

Slope class data is also available from a 1:15000 scale soil survey of the Port Hills (Trangmar, 1991). Comparisons with the GPS ground truth slope map show that 43% of cells are correctly classified, and 90% are correct within one class. Over the 3 km^2 area surrounding the GPS survey areas the Port Hills soil survey map and the ARCTIN interpolated slope map also show good agreement (38% correct and 82% within one class).

5. *Conclusions*

5.1 GPS survey for Groundtruthing DEMs and Slope Maps

The GPS survey was useful as a rapid method for acquiring moderately accurate (±1m) locational data in the x, y and z dimensions. There was some difficulty in acquiring good data in some parts of the terrain studied because of a combination of poor satellite geometry during the middle part of the day and the degree to which the horizon was obscured when surveying in the bottom of the gully running through the study area. However, the ability to use the GPS to reproduce an independent 25 m grid of elevation values matching the contour-based DEMs, provided an objective method for estimating ground truth slopes over the same slope length as the DEM slopes. This method is still subject to errors, but they are more easily quantified than when comparing DEM slopes with those measured by clinometer over varying slope lengths.

5.2 DEM Accuracy

The ARCTIN and GILTRAP interpolation methods provide the most accurate DEMs, however the TOPOGRID method also gives a good surface with the added advantage of being hydrologically correct. However, the analysis suggests that the quality of input data from which the DEM is generated has a more significant effect on DEM quality than do the algorithms employed by the different methods tested.

All DEMs produced from LINZ 20 m contours would meet USGS standards (USGS, 1996) for a level 1 DEM. Twenty-five metres appears to be a practical resolution for DEMs to be used in conjunction with 1:50 000 scale data. Coarser resolutions will result in steadily increasing levels of error, while finer resolutions present substantial data storage and manipulation problems for a database the size of the NZLRI.

5.3 Slope Accuracy

Slopes calculated from DEMs are subject to significant errors, even for DEMs with low *RMSE* and *S* statistics. While in the order of 70% of cells may have slope class correctly assigned to within one class of true slope (i.e., ±7.5°), the magnitude of potential DEM errors which could be propagated through the slope calculation strongly reinforces the need for DEMs to be supplied with some ground truth data and error statistics to quantify the accuracy of the data.

Because of the fractal nature of real hill slopes (i.e., variable at any scale) compared with the slope data derived from contour-based DEMs, which will only show variability at the scale differentiated by the contours, care must be taken in interpreting DEM slope data. The analysis above is suggestive of fuzzy sets, in that the DEM slope estimated for any cell may not exactly match the real slope on the ground at that point, but the relationship between the two may be represented as a membership function. In this case the shape of the membership function could be defined by the data in the classification matrix (table 2). This uncertainty in matching real slope to DEM slope has significance if DEM slope data is to be used to determine the extent of land with slopes exceeding some threshold. For example we might define erosion prone land as areas with slope greater than 15°. Clearly, for a proportion of cells in a DEM slope map with estimated slopes greater than 15°, real slope will be less than 15°. Similarly cells below the threshold might well have a real slope greater than 15°. Any analysis of DEM-based slope data must take this into account.

5.4 NZLRI slope classification comparison

The ARCTIN interpolated slope map (36% correct and 83% within one class) provided a significant improvement in accuracy for the study area over the 1st edition NZLRI data (7% and 35%). This differential is significantly less with simulated 2nd edition standards of NZLRI mapping (31% and 76%). The comparison with the detailed soil survey indicates that DEM-derived slope maps are approximately on a par with data collected in a field survey at 1:15 000 scale (43% and 90%). Slope maps derived from DEMs clearly give a significant improvement in resolution over traditional NZLRI mapping, as well as providing, for the first time, enough information to objectively estimate the magnitude of error in slope maps. These gains must be offset against the "no news is good news" perceptions of some data users, who may conclude that the DEM data is less reliable because the level of error is known, or even worse that the DEM data is 64% wrong because only 36% of cells are correctly classified.

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