International Journal of Applied Earth Observation
and Geoinformation 9 (2007) 235–246

INTERNATIONAL JOURNAL OF
APPLIED EARTH OBSERVATION
AND GEOINFORMATION

www.elsevier.com/locate/jag

Improving a digital elevation model by reducing source data errors and optimising interpolation algorithm parameters: An example in the Loess Plateau, China

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Received 23 December 2005; accepted 30 August 2006

Abstract

A hydrologically correct digital elevation model (DEM) forms a basis for realistic environmental modelling, especially in complex terrain. We have performed a study in the Coarse Sandy Hilly Catchments (CSHC) of the Loess Plateau, China, which demonstrates pragmatic, yet effective methods for improving the quality of the DEM by: (1) identifying and correcting source topographic data errors and (2) optimising ANUDEM algorithm parameters. Improvement in the DEM based on fixing over 1100 errors in the input topographic data, and optimising key ANUDEM parameters was assessed using higher accuracy independent validation of 32 contributing areas and 1474 spot heights, and by semi-quantitative analysis of DEM derivatives produced from ANUDEM and Triangular Irregular Network (TIN) algorithms. Improvement in the ANUDEM DEM over the original TIN DEM was shown where the percentage of the total absolute difference in contributing areas reduced from 10.43 to 3.51%, and the bias between the spot heights and DEM elevations reduced from 45 to 32 m. Large improvement in DEM quality was gained by using ANUDEM instead of TIN, with smaller improvement gained by fixing source data errors, and optimising ANUDEM parameters.

Keywords: DEM; Loess Plateau; ANUDEM; TIN; Profile curvature; Hydrologically correct; Terrain analysis

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1. Introduction

In many developing countries, including China, moderate resolution (10–250 m planar resolution or ≈1:10,000 to 1:250,000 scale) digital elevation models (DEMs) are not routinely available from government mapping agencies, or if they are available, then the quality of the DEM does not often meet the user requirements. Given that in most spatial environmental research (e.g., hydrology, geomorphology, vegetation prediction, and land-use monitoring; see Wilson and Gallant, 2000) hydrologically correct DEMs are a critical input, many researchers in developing countries are forced to generate their own DEMs to meet research needs. A hydrologically correct DEM is one where the river network, contributing areas, and other hydrological metrics

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0303-2434/$ – see front matter
doi:10.1016/j.jag.2006.08.004

are accurately defined from the DEM due to its high degree of landform representation.

There are many relatively new data sources from which to generate moderate resolution DEMs (ranging from ground survey with kinematic GPS to airborne photogrammetry, interferometry, and radar or laser altimetry; see Hutchinson and Gallant, 2000), the most notable recent addition being the Shuttle Radar Topography Mission (SRTM) data. Although SRTM data will provide a solution for some applications, improving DEMs generated through spatial interpolation is still critical as many applications require resolutions finer than those currently available from SRTM, especially for those areas outside of the conterminous US. Also, the SRTM data are a Digital Surface Model (DSM) because they are a representation of the surface including what is above the ground (e.g., vegetation, buildings, etc.), whereas a DEM is a representation of the ground elevation, excluding such features. Removing surface features from a DSM (i.e., making a DEM from a DSM) is a complicated task, which is not yet commonly achieved at a broad scale (e.g., Hofton et al., 2006). This means that even since the recent availability of SRTM data, by far the most effective and common way to generate a DEM is by interpolation of digital topographic data. These data typically include contours, spot heights, rivers, and lakes, and while the use of such topographic data may appear straightforward, results can vary greatly as a function of the quality of the input data, the algorithm used, and the parameters input to the algorithm. For example, while a DEM can be generated using a Triangular Irregular Network (TIN) approach on contour and spot height data, the resultant DEM may not be hydrologically correct. This can be seen by the widespread presence of artificial features such as flat hill tops, triangular hill slopes, and spurious triangular-shaped sinks or peaks resulting in incorrectly derived stream networks, contributing areas, and catchment boundaries. Additionally, surfaces of slope and aspect usually contain obvious errors when using a DEM generated by TIN. To meet the challenge of creating hydrologically correct DEMs from digital topographic data, an algorithm developed by the Australian National University (called ANUDEM) has evolved over the last 20 years (Hutchinson, 1988, 1989, 2004).

One advantage of using an interpolation program such as ANUDEM is that the digital topographic data required are readily available in many developing countries, and usually at various resolutions. In China, the benefits of using ANUDEM to generate hydrologically correct DEMs have not been fully realised (Zhou et al., 2002) as DEMs have been primarily generated using the TIN algorithm. A DEM is a fundamental dataset in environmental research and management, and improving it will improve all subsequent spatial analysis conducted using it. For example, severe soil erosion rates (e.g., 20,000–60,000 t km^{-2} year^{-1}; Shi and Shao, 2000; Xiang-zhou et al., 2004) in the Coarse Sandy Hilly Catchments (CSHC) of the Loess Plateau, China (Fig. 1), have partly resulted in the Chinese Central Government establishing the "Grain for Green" project (Tui Geng Huan Lin) with the aim to return cultivated land with slopes of 25° or more to forest (e.g., Wenhua, 2004; Xu et al., 2004; Yang, 2004). Targeted and effective planning of such a broad-scale re-vegetation program will require an assessment of vegetation suitability (Li et al., 2005; McVicar et al., 2005, in press), and this in turn relies upon having access to a high quality, hydrologically correct DEM.

The current research outlines simple strategies to ensure high DEM quality when using ANUDEM by: (1) identifying and correcting errors in the original digital topographic data and (2) developing methods to optimise key ANUDEM parameters. Validating the resultant DEM improvements were achieved using data frequently accessible in developing countries, including comparisons of: (1) contributing areas of hydrologic gauging stations to an independent validation dataset derived from finer scale paper maps and (2) DEM elevations to spot heights from finer scale digital topographic data. Comparisons are also made from slope and stream DEM output for a small representative test area. The methods described here are as generic as possible so the underpinning ideas can be transferred to other interpolation algorithms without major modification.

2. Methods

The three main topics of this section describe the methods used to correct errors in the source data, optimise key ANUDEM parameters, and assess subsequent DEM improvement. All corrections made to the CSHC source datasets were performed over the entire CSHC area. However, to assess the influence of input data corrections and the optimising of ANUDEM parameters, we limited our processing to the YanHe Basin (YHB) test area, see Fig. 1. The YHB test area is representative of the overall landscape, and is a small enough area to create a 100 m resolution DEM using ANUDEM in 1/16 the time it takes for the entire CSHC.

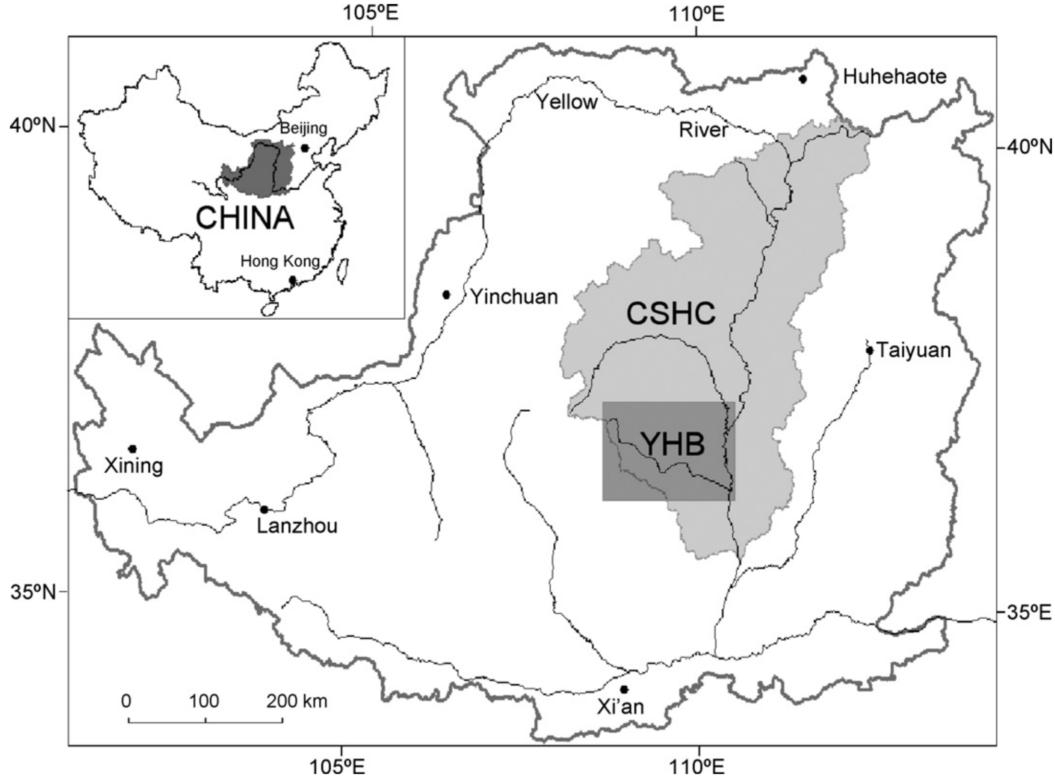

Fig. 1. On the main map the light shading shows the location of the 112,728 km^2 Coarse Sandy Hilly Catchments (CSHC), with the 20,169 km^2 YanHe Basin (YHB) test area indicated by the dark grey rectangle. The thick grey line represents the boundary of the 623,586 km^2 Loess Plateau that is located on the middle reaches of the Yellow River and shaded in the inset map of all China.

2.1. Correcting source data

For the CSHC, the data for the thirty-six 1:250,000 digital topographic map sheets containing all contours, spot heights, and rivers published by the National Geographic Centre of China (NGCC) between 1975 and 1986 were used. These data were initially used to generate a TIN DEM, however there were obvious errors in the results that necessitated the use of ANUDEM. As ANUDEM outputs several files that can be used for identifying errors in the source data and for optimising interpolation parameters, these were used to further improve the final ANUDEM DEM. An iterative process was used to improve the quality of the input topographic data with careful analysis of the ANUDEM output and diagnostic files undertaken to identify problems that were subsequently corrected (where possible) in the input topographic data. This process had to be iterative as large errors can mask smaller errors, and not all errors will be detected in a single run of ANUDEM.

The input source data to ANUDEM consisted of four basic datasets: contours, spot heights, rivers, and lakes and reservoirs. Throughout the many iterations of processing data over the entire CSHC area, several problems with input topographic data were observed and subsequently resolved. The most common were: (1) attribute and positional errors of both contours and spot heights and (2) various characteristics of the river and lakes dataset. The process of identifying and correcting these problems was automated wherever possible. The impact of data corrections on the resulting DEM quality was assessed by monitoring the number of sinks and the average number of cells per sink in the output DEM after each major correction was made.

2.1.1. Contour and spot height correction

Contour and spot height errors were addressed using two approaches. The first was to compare large residual points (output by ANUDEM in the log file) to the DEM value at the same location; this identified mislabelled spot heights and/or contours as well as misplaced spot heights and incorrectly digitised contours. The second approach was to identify inordinately large slopes from the output DEM in order to detect additional mislabelled contours that were not necessarily near a spot height.

To enact the first error identification approach, spot heights that had a large residual error (Hutchinson, 2004) greater than or equal to 50 m were examined as this was the expected vertical accuracy of the DEM (USBB, 1947; NMCA, 1953). In the entire CSHC 9135 spot heights existed, 2097 of these were identified as residuals by ANUDEM. Of these residuals, 155 had a difference between the original elevation and the DEM elevation of greater than or equal to 50 m, and 90 of these required correction. This method of checking ANUDEM residuals was a good way to identify possible errors near spot heights. As there were spot heights distributed all around the study site, this method provided good coverage of the site; see Yang et al. (2005) for full details.

To implement the second error identification method, the slope of the output DEM for the entire CSHC area was calculated and inspected for areas of exceedingly large slopes, defined here as slopes >39° from horizontal (this threshold would change for varying resolution DEMs). These very large slopes invariably identified mislabelled contour lines, as they predominantly occurred in the same shape as a contour line (or part of a contour line). This approach found >50 mislabelled contours in areas irrespective of their proximity to spot height data, thus it was a good complement to the residual spot height methodology described above. Fig. 2 is an example of a slope surface where several mislabelled contours were identified and corrected.

2.1.2. River and lake correction

Running ANUDEM without separating the rivers and lakes into separate inputs resulted in inappropriate processing of the DEM, so based on the NGCC codes, these were separated. Many man-made canals were located along some of the larger rivers and using these to enforce drainage was problematic (Hutchinson, 2004), so man-made canals were removed from the rivers dataset. In the original topographic river network data, about one-half of the rivers (or certain segments of the rivers) were flowing in the wrong direction. Due to the numerous lines (>40,000), it was not feasible to check and flip these manually, so potentially wrong-flowing river segments were programmatically flipped. After automated flipping of river segments, and additional program identified that 1057 possible errors remained. Each of these potential errors was manually checked and 805 were confirmed as errors, which were manually flipped; see Yang et al. (2005) for full details. Finally, many large rivers were represented by two lines (one on each bank) as opposed to a single centreline that was used for smaller rivers. This posed a problem with ANUDEM processing and needed to be fixed. As using the ArcInfo *centreline* command was found to provide insufficient results, a series of ArcView avenue scripts were created in order to help define these centrelines; see Yang et al. (2005) for full details.

2.2. Optimising key ANUDEM parameters

Three ANUDEM Version 5.1 parameters were evaluated in order to define optimal values for the CSHC 1:250,000 dataset. The parameters include: (1) output grid resolution, (2) number of iterations, and (3) the amount of profile curvature. Optimising these three parameters was where most potential gains in accuracy were expected, and it was recommended that default values be used for all other ANUDEM parameters (Hutchinson, personal communication).

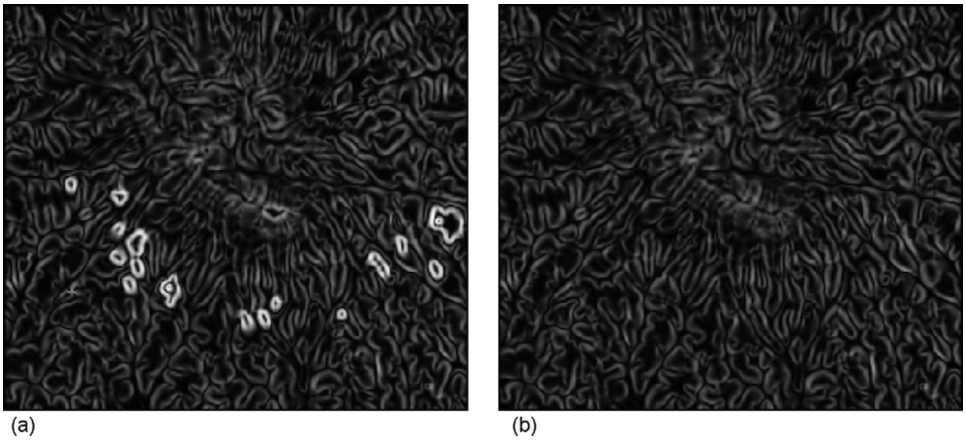

Fig. 2. The slope surface calculated from a DEM generated using uncorrected contour data is shown in (a) where several incorrectly labelled contours were identified by grid cells with extremely high slopes (bright white grid cells have slopes of 57°). This allowed the mislabelled contours to be selected and corrected. The realistic slope surface calculated from a DEM generated using corrected contour data is shown in (b). The location of this area and full details are provided in Yang et al. (2005).

2.2.1. Spatial resolution

The method of Hutchinson and Gallant (2000) was performed in which the root mean squared difference (RMSD) slope of interpolated DEMs was calculated, and allowed for selection of the final output grid cell resolution. An additional analysis of the rate of change between successive spatial resolutions was also performed.

2.2.2. Number of iterations

The number of iterations in ANUDEM is a key parameter that governs three metrics of DEM quality, they are: (1) ‘number of new lines’, (2) ‘number of drainage enforcements’, and (3) ‘number of sinks’. ANUDEM initially produces a low resolution DEM that is stored in RAM. A series of higher resolution DEMs are then produced in RAM by progressively halving the resolution of the output cells, concluding with a DEM possessing the user specified resolution that is written to disk. The theory underpinning the use of this ‘nested grid SOR (successive over-relaxation) iterative method’ is provided by Hutchinson (2000). For each grid resolution, the ‘number of new lines’ generated to represent the landscape between the preceding and current resolution DEMs are reported in the ANUDEM log file. A small ‘number of new lines’ values indicate that the two DEMs are stable, as few new lines were added to describe the profile between ridgelines and streamlines even though the resolution was halved. If this value is not small (a typical low value that may be deemed appropriate is less than 10), then the ANUDEM user specified ‘number of iterations’ may need to be increased. The number of drainage enforcements shows that ANUDEM is enforcing drainage at places other than where the input stream data exits, so a high value represents a well-connected river network. Finally, a low number of sinks should, generally speaking, demonstrate that the output DEM is not riddled with errors and that it has good continuity with respect to flow and contributing areas. These three metrics were expressed as a function of the number of iterations (varying from 10 to 120 in increments of 10) so that an optimal number of iterations could be determined with respect to all three of these other variables.

2.2.3. Profile and total curvatures

The profile curvature, defined as the curvature of the fitted surface in the downslope direction (Gallant and Wilson, 2000), is newly introduced in Version 5.1 of ANUDEM (Hutchinson, 2004). The profile curvature, which is locally adaptive (Hutchinson, 2000), can be used to partly replace the total curvature, with profile curvature allowing better representation of rapid changes in gradient (a common phenomena in the CSHC). In ANUDEM Version 5.1, the relative amounts of total and profile curvature are controlled by the user specifying the ‘2nd roughness penalty’; herein termed 2nd roughness. Values for the 2nd roughness can range from 0.0 to 0.9; a value of 0.0 (the default) means only total curvature is used, whereas a value of 0.9 means that 0.1 of total curvature and 0.9 of profile curvature is used. The impact of changing the 2nd roughness was examined as a function of the same three metrics as discussed previously. That is, number of last new lines, number of drainage enforcements, and number of sinks were used to optimise the 2nd roughness. Values for the 2nd roughness were varied between 0.0 and 0.9 in increments of 0.1.

2.3. Assessment of DEM improvement

Without comparing DEM quality assessment before and after correcting the input datasets and optimising the ANUDEM parameters, it would not be known whether performing such laborious and time-consuming actions were necessary. Therefore, three 1:250,000 scale DEMs were generated over the entire CSHC for use in DEM quality assessment: (1) the original DEM generated using the TIN algorithm with default parameters and uncorrected source data, referred to as TIN_def, (2) the DEM generated using ANUDEM with default parameters and uncorrected source data, referred to as ANUDEM_def, and (3) the final DEM generated using ANUDEM with optimised parameters and corrected data, referred to as ANUDEM_opt. DEM improvement was assessed from these three DEMs in three ways including: (1) comparing the contributing areas of 32 hydrologic stations to those calculated from 1:50,000 paper maps, (2) assessing the bias and RMSD between the 1474 independent validation spot heights from the 1:100,000 YHB data, and (3) summarising some basic statistics of a small test area within the YHB of slope and stream output.

All three DEMs were generated with the optimal spatial resolution (of 100 m; see Section 3.2.1). To generate TIN_def, the ArcInfo TINLATTICE command was used with the weed tolerance = 1, proximal_tolerance = 0.5, and with no z_factor applied to the source data containing errors. To develop ANUDEM_def the uncorrected source data was used and the number of iterations and 2nd roughness penalty were set to the default values of 20 and 0.0, respectively. ANUDEM_opt was generated using the corrected source data and the optimum values for the number of iterations, and 2nd roughness (40 and 0.8, described in Sections 3.2.2 and 3.2.3).

2.3.1. Independent validation of contributing areas

Contributing areas for 32 hydrologic gauging stations were obtained from the Yellow River Conservation Commission (YRCC, 1982). They were calculated from 1:50,000 scale paper maps using a planimeter. These data provide an independent validation to assess the three various 1:250,000 scale CSHC DEMs. Several summary statistics were derived between the validation contributing areas and those determined from the three DEMs. These include the maximum, minimum, mean, and standard deviation of the difference, as well as the bias

$$\text{Bias} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)\right] \tag{1}$$

the RMSD

$$\text{RMSD} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5} \tag{2}$$

the total cumulative area (TCA)

$$\text{TCA} = \frac{\sum_{i=1}^{n} O_i}{\sum_{i=1}^{n} P_i} \tag{3}$$

and the total absolute difference (TAD)

$$\text{TAD} = \frac{\sum_{i=1}^{n} |O_i - P_i|}{\sum_{i=1}^{n} P_i} \tag{4}$$

where P_i was the set of reference contributing area data, O_i the set of DEM-derived contributing area data, and n equals 32. A pair-wise t-test was also performed between the reference dataset and each DEM dataset with resultant values indicating the probability that the DEM-derived set of contributing areas was from the same population and had the same mean as the reference data. TCA and TAD are reported as percentages.

2.3.2. Independent validation of spot heights

The elevations of all available spot heights from the 1:100,000 YHB source data (1474) provided a different independent source of validation for the three 1:250,000 scale CSHC DEMs. Slightly modifying the method developed by Van Niel and McVicar (2001) meant that the positional accuracy between the two datasets was minimised by applying a shift of 121 m and 238° to the YHB dataset; see Yang et al. (2005) for full details. The bias and RMSD were calculated (see Eqs. (1) and (2)), where in this case, P_i was the set of non-common spot heights from the 1:100,000 YHB data, O_i was the maximum elevation in each 3×3 window from the three resultant DEM output generated from the 1:250,000 CSHC topographic source data centred on the corresponding locations, and n was 1474.

2.3.3. Semi-quantitative assessment of slope and stream outputs

Finally to provide semi-quantitative assessment of the three 1:250,000 DEMs, slope, and stream output were compared for a 248.4 km^2 focus area within the YHB; the location of the focus area is given in Yang et al. (2005). Stream networks were also derived for this focus area using a flow accumulation threshold of 20 cells. A visual comparison as well as a quantitative analysis of the histograms of the slope datasets and the Strahler stream orders for the stream networks provided for an assessment of the various DEMs.

3. Results and discussion

3.1. Correcting source data

The corrections to the source data showed an improvement in DEM quality as measured by the number and extent of sinks in the output DEMs. In the YHB test area before correcting source data errors this original DEM had 2207 sinks with an average of 8.79 cells per sink that were greater than 10 m depth. This reduced to 526 sinks (again greater than 10 m depth) with an average of 2.31 cells per sink after data errors were corrected; see Yang et al. (2005) for full details. We note that relying too much on sink number and size as metrics of DEM data quality is unadvisable because sinks are not always caused by an error in the DEM. Quantifying the number of sinks and their average size allowed for a direct comparison between various tests without requiring independent validation data. An additional way of identifying streams that flow in the wrong direction would be to overlay sinks on the stream network. Sinks located at the end of a stream would likely indicate that the stream is flowing in the wrong direction.

3.2. Optimising key ANUDEM parameters

3.2.1. Spatial resolution

Contrary to the example in Hutchinson and Gallant (2000) no distinctive break-point was present in our plot of RMS slope versus spatial resolution (Fig. 3a). As the CSHC is a landform of rapidly changing slopes (see Fig. 3 of Yang et al., 2005) we wanted to generate a DEM with

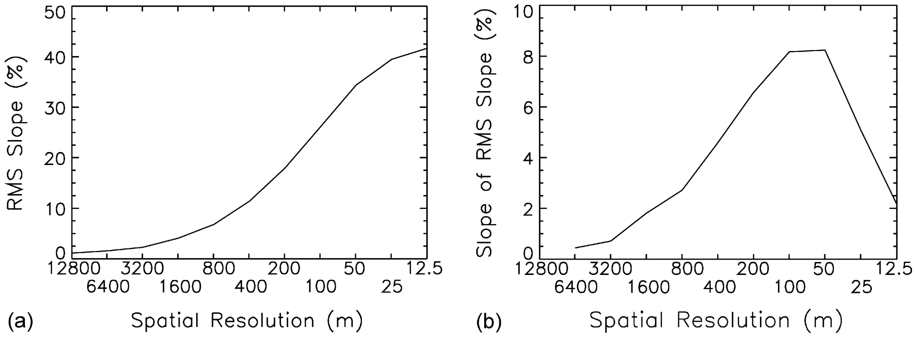

Fig. 3. Impact of spatial resolution for the YHB test area on: (a) the RMS of the slope and (b) the rate of change (or slope) of the RMS slope data presented in (a).

the highest resolution that the input data could readily support. Consequently, we assessed the rate of change of RMS slope between successive spatial resolutions (Fig. 3b). From this analysis, we concluded that an output resolution between 25 and 100 m provided the optimal information content from the 1:250,000 input data. The high input data density of the CSHC (Yang et al., 2005) easily supports a 100 m resolution DEM; this is, higher than the 250 m value calculated from the commonly used heuristic of Hutchinson (personal communication) defined as 10^{-3} of the input map scale.

3.2.2. Number of iterations

Fig. 4a illustrates that from 40 iterations onwards a satisfactorily low number of 'last new lines' is achieved. It should be noted that the improvement from 10 to 20 iterations was the most dramatic (Fig. 4a), the improvements beyond the default value of 20 were marginal, yet important, for our case. Given that the number of iterations is linearly related to the computational time, we decided that setting the ANUDEM maximum number of iterations user input to 40 was best to allow the representation of the landscape to become stable given the complexity of the landforms within the CSHC, while finishing in reasonable time. Further analysis of the impact of the 'maximum number of iterations' user input on two ANUDEM characteristics, the number of drainage enforcements and number of sinks, are shown in Fig. 4c and e, respectively; a reciprocal relationship between the number of drainage enforcements and number of sinks is seen. From the results presented in Fig. 4a, c, and e, we see that using 40 iterations is a pragmatic balance that minimises the 'number of last new lines' and sinks, while enforcing drainage, and does not take too long to process.

3.2.3. Profile and total curvature

For the YHB test area, the influence of the relative amounts of total and profile curvature (altered by incrementing the 2nd roughness in 0.1 steps from 0.0 to 0.9) was determined for the 3 previously specified metrics reported by ANUDEM. To ensure that the resultant DEM was both stable and as hydrologically correct as possible we aimed to minimise both the number of new lines (as this shows a stable DEM) and the number of sinks (as this is a metric of general improvement in data quality). While the goal was not necessarily to maximise the number of drainage enforcements, a high drainage enforcement value shows that the output river network should be well connected. The analysis of these three metrics suggested that using a 2nd roughness of either 0.8 or 0.9 provided optimal results (Fig. 4b, d, and f). We decided that 0.8 was preferred in this landscape due to the stability of the ANUDEM algorithm being slightly higher, indicated by the minimum number of last new lines.

Of note is the relationship between the number of drainage enforcements to the number of sinks; this ratio became larger when the 2nd roughness was >0.4. This meant that more gullies and ridges would be generated, so the resultant DEM would better represent the complex landforms found in the CSHC. Yang et al. (2005) show that the more profile curvature used, the steeper the DEM representation of landform becomes. These analyses also indicated that a high 2nd roughness should be used in the CSHC (e.g., a 2nd roughness of 0.8 or 0.9) in order to increase the slope of the profile and better match the relief of the site.

3.3. Validation of DEM improvement

3.3.1. Independent validation of contributing areas

Results in Table 1 show a large difference between the two algorithms (compare the TIN output with either of the ANUDEM outputs), and smaller differences due

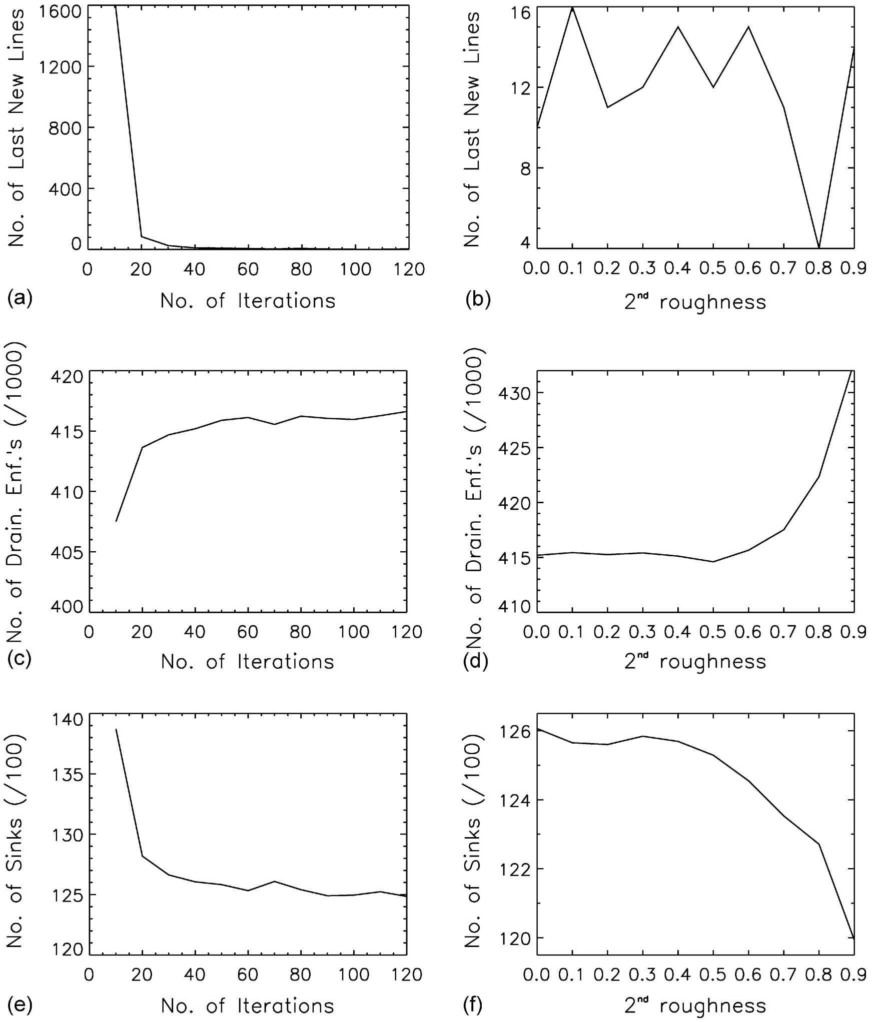

Fig. 4. The number of last new lines, number of drainage enforcements and number of sinks are shown as a function of the number of iterations in (a, c, and e) and as a function of 2nd roughness in (b, d, and f).

to source data error correction and algorithm parameter optimisation (compare ANUDEM_def and ANUDEM_opt in Table 1). It must be noted that the contributing area metric is generally not sensitive to localised errors and the optimisation of the parameters tested here, as even if a hill-slope is grossly in error (or if its profile is unrealistic), it will often still contribute to the area below it.

Table 1

Summary statistics for the 32 reference contributing areas, and the same areas derived from the three (1:250,000) DEMs

	Reference	TIN_def	ANUDEM_def	ANUDEM_opt
Max. (km^2)	30,217	30,264	30,628	31,058
Min. (km^2)	187	120	183	185
Mean (km^2)	3770	3576	3752	3787
S.D. (km^2)	6363	6499	6518	6619
Bias (km^2)	–	194	18	−17
RMSD (km^2)	–	837	289	361
t-Test (proportion)	–	0.20	0.73	0.79
TCA (%)	100.00	94.86	99.53	100.46
TAD (%)	0.00	10.43	3.03	3.51

As TIN_def and ANUDEM_def use default algorithm parameters and the same uncorrected input data they allow a direct comparison of TIN and ANUDEM algorithms for our study site. There was a vast improvement in the contributing area metric when using ANUDEM as opposed to TIN, see Table 1. Specifically, the mean and S.D. of ANUDEM_def were much closer to the reference data, and the bias and RMSD of ANUDEM_def were much lower than TIN_def, showing a better match over the 32 contributing areas. The *t*-test statistic was a pair-wise test that defines the probability that the set of contributing areas from each DEM was from the same population and had the same mean as the reference data. The *t*-test statistic showed a vast improvement when using the ANUDEM algorithm over the TIN algorithm and also illustrated that ANUDEM_opt was better than ANUDEM_def. Additionally, the two normalised area calculations (TCA and TAD) revealed that the sum of the ANUDEM contributing areas matched the reference data better than the results from the TIN (Table 1) with little difference between the two DEMs generated with ANUDEM. In contrast with the contributing area analysis, the following spot height assessment is expected to be sensitive to the correction of localised errors and optimisation of parameters between the two ANUDEM DEMs.

Table 2

Summary statistics (Bias, RMSD, and S.D.) for the 1474 non-common spot heights in the YHB test area for the three (1:250,000) DEMs

	TIN_def	ANUDEM_def	ANUDEM_opt
Bias (m)	45	37	32
RMSD (m)	55	47	43
S.D. (m)	32	29	29

3.3.2. Independent validation of spot heights

Results presented in Table 2 show the improvement when using ANUDEM over the TIN, but unlike the contributing area assessment, also show that ANUDEM_opt was superior to ADUDEM_def. That is, all three statistics reduce between TIN_def and ANUDEM_def and then the bias and RMSD again reduce between ANUDEM_def and ANUDEM_opt.

3.3.3. Semi-quantitative assessment of slope and stream outputs

Again, these results showed the biggest improvement between TIN_def and ANUDEM_def, with a smaller improvement between ANUDEM_def and ANUDEM_opt. This is especially noticeable in the histograms of the slope outputs (Fig. 5d) as TIN_def had an inordinate number of cells with zero slopes and a

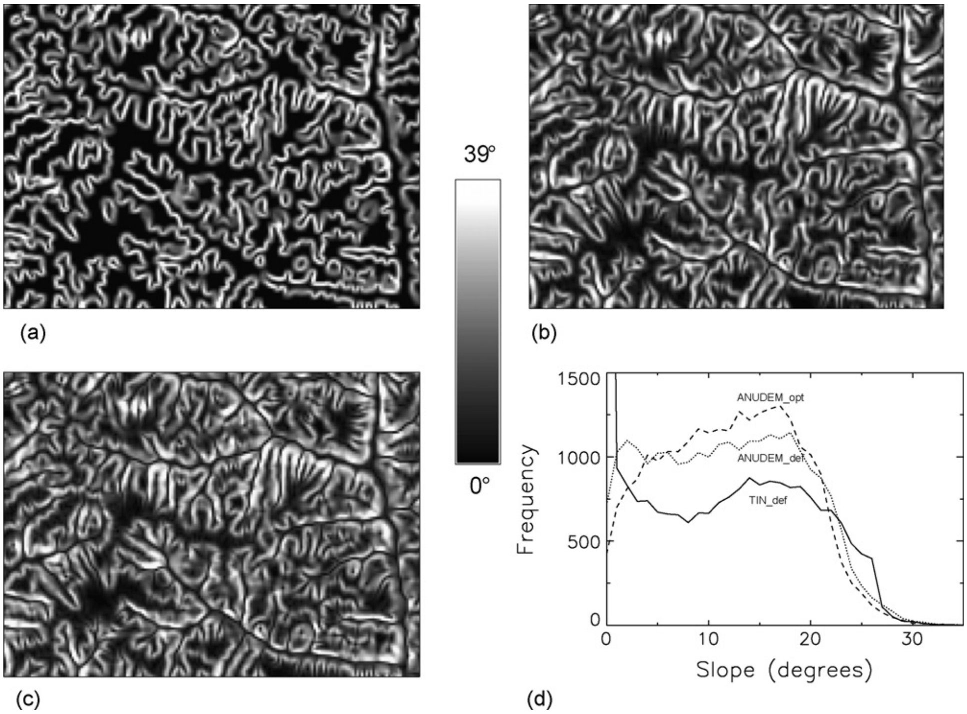

Fig. 5. Output slope surfaces, in degrees from horizontal, for (a) TIN_def, (b) ANUDEM_def, and (c) ANUDEM_opt. The histogram of these three DEMs are shown in (d). The number of zeros for TIN_def extends to 6035 cells.

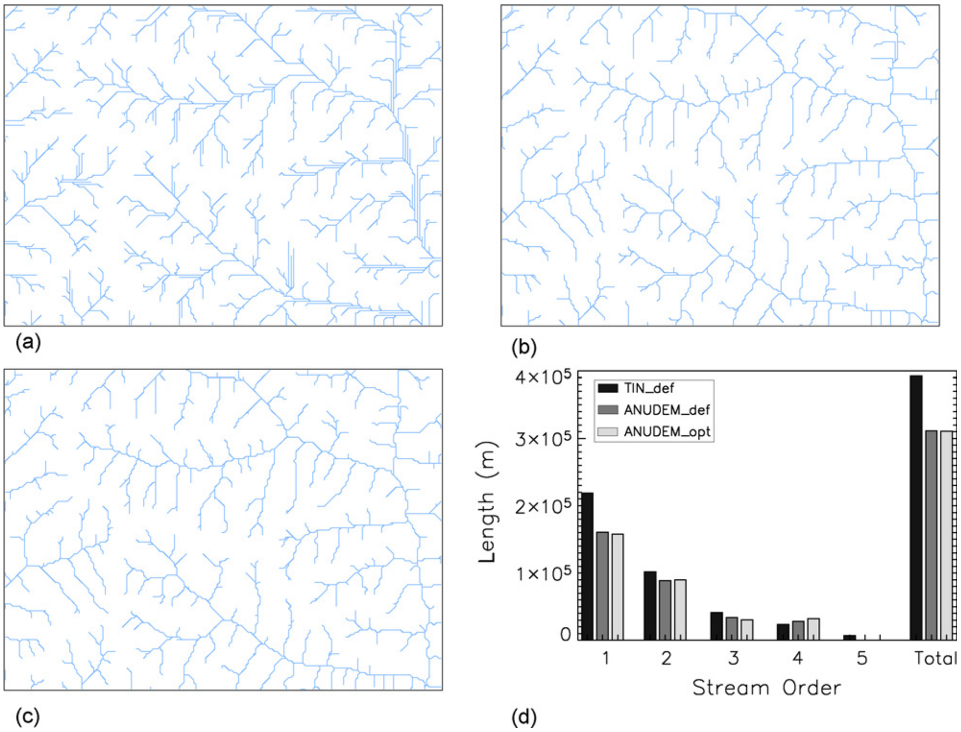

Fig. 6. Output rivers from DEM for (a) TIN_def, (b) ANUDEM_def and (c) ANUDEM_opt. The length of Strahler stream orders and their combined total length is shown in (d).

bimodal distribution with many more cells having high slopes. For TIN_def, ANUDEM_def, and ANUDEM_opt the number of cells with zero slopes were 6035 (24.3%), 714 (2.9%), and 422 (1.7%), respectively. The number of grid cells with slopes greater than 23° from horizontal were 2151 (8.7%), 1612 (6.5%), and 1121 (4.5%), respectively. The improvement between ANUDEM_def and ANUDEM_opt slopes was also evident in the histograms as ANUDEM_opt revealed fewer 100 m cells with lower slopes which is more realistic for this landscape, as well as a slightly more continuous surface of slope (Fig. 5d).

The same general progression of improvement seen from the slope assessment was also demonstrated in the stream output; the TIN_def streams revealed many unrealistic straight and parallel streams (Fig. 6a), and these were vastly improved in the ANUDEM_def output (Fig. 6b). Again, smaller improvement was seen between ANUDEM_def and ANUDEM_opt (Fig. 6c). The vast improvement in the stream network derived from ANUDEM_def, compared to those derived from TIN_def, reveals that ANUDEM modelled the complex landforms of the CSHC better than the TIN algorithm. This pattern was quantified by summarising the length of the various Strahler stream orders and their total length (Fig. 6d). As can be seen in the figure, the unrealistic TIN_def resulted in a great increase in the total stream length, largely due to many more first order streams when compared to either of the ANUDEM DEMs (Fig. 6d). The difference in stream length was much smaller between ANUDEM_def and ANUDEM_opt (Fig. 6d). The total length of the streams from the three DEMs were 393, 312, and 311 km for TIN_def, ANUDEM_def and ANUDEM_opt, respectively. The length of the first order streams was 219, 161, and 158 km, respectively. Table 3 shows that there were many more 1st, 2nd, and 5th order streams present in the stream network derived from TIN_def compared with those generated from ANUDEM_def and ANUDEM_opt.

Table 3
The number of streams in each Strahler stream order class for the three (1:250,000) DEMs

Stream order	TIN_def	ANUDEM_def	ANUDEM_opt
1	371	269	274
2	177	125	128
3	75	62	59
4	49	53	59
5	15	1	1
Total	687	510	521

4. Conclusions

This paper documents how input elevation data quality was iteratively improved by using ANUDEM Version 5.1 output data-files and diagnostic log-files to identify and correct over 1100 errors in the 1:250,000 data for the CSHC on the middle reaches of the Yellow River Basin in China. This, coupled with optimisation of several key ANUDEM parameters – specifically the spatial resolution (100 m), number of iterations (40), and the 2nd roughness (0.8) controlling the amount of profile curvature – meant that the resultant DEM for the CSHC was of high quality as it was generated using the current best available topographic data and best practice algorithm.

Comparison of the two ANUDEM DEMs allowed for a direct assessment of DEM improvement due to implementing error correction and parameter optimisation. The analysis of the 1474 spot heights showed that these actions resulted in a reduction in bias from 37 to 32 m. As expected, the analysis of the 32 contributing areas did not reveal such obvious improvements as this metric is not as sensitive to these enhancements (e.g., the bias changed from 18 to -17 km^2). DEM improvement due to error reduction and parameter optimisation was also seen in the analysis of slopes as the optimised DEM had fewer zero slopes (1.7% compared to 2.9%) and fewer high slopes (4.5% compared to 6.5%). This result suggested that subtle, yet important, improvements were made by correcting errors in the source data and optimising several key ANUDEM parameters.

Direct assessment of DEM improvement solely due to the algorithm was performed by comparing a TIN DEM (generated using uncorrected data and default parameters) to the ANUDEM DEM (also generated using uncorrected data and default parameters). All analyses showed that the ANUDEM algorithm produced a better DEM than the TIN algorithm. For example, in the spot height analysis the bias reduced from 45 to 37 m, and the RMSD reduced from 55 to 47 m by using ANUDEM. Likewise, in the analysis of the 32 contributing areas, the bias reduced from 194 to 18 km^2, and the RMSD reduced from 837 to 289 km^2 by using ANUDEM instead of TIN. Additionally, almost 25% of the TIN DEM had zero slopes compared to less than 3% in the ANUDEM default DEM, which also made the TIN slope image look unrealistic. The TIN also produced 35% more streams than ANUDEM, with many of these being unrealistically straight, short, and running parallel to other streams. These results illustrated that the DEM generated using the TIN algorithm was inferior compared to that generated using ANUDEM.

The methods and experience developed here can be used with other contour and spot height datasets available for parts of the Loess Plateau (where higher resolution data are available—see Yang et al., 2005), in China, and elsewhere to generate best practice DEMs from digital topographic datasets. This study outlined practical and generically applicable methods for improving and independently assessing DEM quality; these methods are particularly useful for environmental research projects in developing countries.

Acknowledgements

The research was funded by Australian Centre for International Agricultural Research (ACIAR), specifically project LWR/2002/018, Chinese Academy of Sciences (CAS) Institute of Soil and Water Conservation, CSIRO Land and Water, and CAS Innovation Project (Impacts of Soil and Water Conservation on Environmental Factors in Loess Plateau of China: Project of Knowledge Innovation Program of CAS, KZCX3-SW-421). Additional ACIAR project details can be found at http://www.clw.csiro.au/ReVegIH/. We received helpful comments from Dr. John Gallant and Mr. Trevor Dowling, both from CSIRO Land and Water Canberra, while performing this research. Dr. Yun Chen and Mr. Ron DeRose, also both from CSIRO Land and Water Canberra, are to be thanked for assisting us to use some of the SedNet suite of tools to determine the sub-catchments. Mr. Cade McTaggart, from Centre for Resource and Environmental Studies, Australian National University, Canberra, provided assistance by ensuring that we had the latest version of ANUDEM. Thanks to the two anonymous reviewers and editor who all made insightful comments that improved an earlier draft of this manuscript.

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