Study on Accuracy of 1-Degree DEM Versus Topographic Complexity Using GIS Zonal Analysis

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Abstract: Zonal analysis in geographic information systems is a useful and convenient tool to study the accuracy of the digital elevation model (DEM) in terms of topographic complexity, which is defined in this paper as the change in terrain slope or slope change. The accuracy of the U.S. Geological Survey 1-degree DEM over two test areas is studied by comparing it with the USGS 7.5-min DEM. The statistical quantities of the DEM errors are studied and modeled using various mathematical functions. It is shown that the standard deviation of the 1-degree DEM can be largely approximated with a linear function of the slope change, while its minimum and maximum errors remain almost unchanged and occur in all slope change zones as a behavior independent of the terrain complexity.

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Introduction

At least two nationwide raster DEMs (Digital Elevation Model) are available in the United States. One is at a spatial resolution of 3 arc seconds; the other is at 30 m. Because the former is catalogued according to the 1-degree 1:250,000 topographic quads, it is also often called a 1-degree DEM. For the same reason, the latter is called a 7.5-min DEM, because it is catalogued based on the 7.5-min topographic quads (USGS 1998). Both DEMs cover the entire United States and are made available for free to the public.

Different methods have been used to collect DEMs in the United States. One common method is photogrammetry, which has been primarily used to collect 7.5-min DEM. This was carried out in three operational modes: (1) using automatic photogrammetric equipment, e.g., Gestalt Photo Mapper; (2) manually profiling the stereoscopic model; and (3) interpolating the stereoscopically traced contours. Another method is to digitize contour lines from topographic and/or hydrographic maps. This method has been used to collect both the 1-degree and 7.5-min DEMs and remains the current DEM collection method in the U.S. Geological Survey (USGS). In recent years, lidar (light detection and ranging) technology has become popular for elevation data collection. It transmits laser pulses to the ground and measures their two-way travel time to obtain the distance to the ground. Using the onboard global positioning system (GPS) receiver and inertial navigation system (INS), the post-processing operation will then calculate the three dimensional (3D) coordinates of the topographic surface. Further filtering operations are needed to obtain the bare ground elevation by removing vegetation and buildings in the original lidar data (Fowler 2001).

The DEM quality is of a primary interest and concern for both DEM producers and users and has been studied by a number of authors in the past years. Brown and Bara (1994) report on the existence of systematic errors in the 7.5-min DEM. The accuracy of the DEM and its derivative topographic characteristics, such as slope and aspect, are studied by Bolstad and Stowe (1994). Garbrecht and Starks (1995) report on an unsuccessful utilization of the 7.5-min DEM for drainage analysis due to its insufficient quality. Guth (1999) reports that the contour lines of topographic maps used to generate a DEM may have an imprint (so called ghost line or ghost effect) in the resultant DEM. Rees (2000) uses the semivariogram to study the theoretical accuracy of DEM interpolation under certain assumptions. Farrington and Shan (2001) report on the quality of the DEMs over most of the state of Indiana and observe abnormal processing effects, including blunders, border misalignment, horizontal shift, striping, as well as ghost lines. Daniel and Tennant (2001) describe the factors that affect DEM quality and present a thorough comparison between photogrammetry and lidar for DEM generation.

Unlike the aforementioned existing studies, this research looked at the relationship between the DEM's accuracy and the topographic complexity. Both the 1-degree and 7.5-min DEMs over two areas in Indiana are used for this study. Because the nominal accuracy (standard deviation of 7.5 m) of the 7.5-min DEM is much higher than the nominal accuracy (standard deviation of 30 m) of the 1-degree DEM (USGS 1998), the former is used as a reference or ‘‘ground truth’’ in this study. This selection of the ground truth is also made because the 7.5-min DEM is the most popular and accurate available DEM over the entire country. To facilitate our study, we first define the slope change or curvature of the terrain as the topographic complexity measure. Then, the DEMs over the entire study areas are classified into several (in this study 5 or 6) zones according to the magnitudes of the slope change. All DEM cells, regardless of their adjacency, whose slope changes are within a predefined range, will form one zone. The statistical quantities, including minimum, maximum, mean, and

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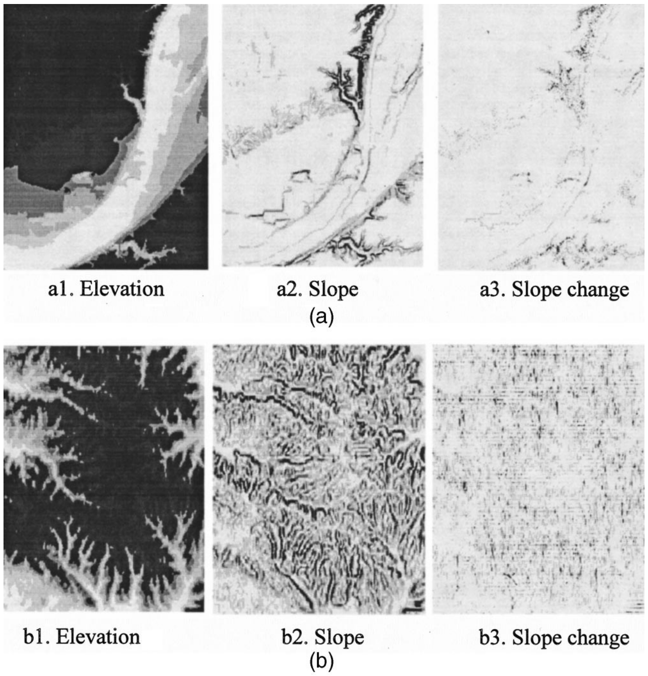


Fig. 1. Terrain and its complexity (7.5-min DEM). The graphics are shade coded in such a way that the darker the shade, the larger the values, (a) flat area; (b) rough area

standard deviation of the elevation differences between the interpolated 1-degree DEM and the 7.5-min DEM are then studied according to the slope change zones. In addition, we used various forms of mathematical expressions to approximate the error trend of the 1-degree DEM.

Approach and DEM Data

It has long been known that the accuracy of elevation data collection as well as interpolation is affected by topographic complexity (Burrough and McDonnell 1998). In order to quantitatively characterize the terrain complexity, we introduced the slope change or curvature as the measure of terrain complexity. Assume a quadratic surface with its coordinate origin at the DEM cell to be studied being used to approximate the local topography. The surface takes the form (Zevenbergen and Thorne 1987)

$$Z=aX^2Y^2+bX^2Y+cXY^2+dX^2+eY^2+fXY+gX+hY+i \tag{1}$$

where Z=the elevation; (X,Y) are the planimetric coordinates; and $a,b,\ldots i$ are the coefficients of the quadratic polynomial.

Table 1. Zone Definition and Slope Change

	Flat Area		Rough Area	
Zone number	Number of cells	Slope change range (degree/100 m)	Number of cells	Slope change range (degree/100 m)
1	34,216	0–0.4	5,129	0–0.5
2	14,863	0.4–0.7	32,607	0.5–1.0
3	2,828	0.7–1.0	13,481	1.0–1.5
4	1,250	1.0–1.3	4,972	1.5–2.0
5	1,107	1.3–5.5	1,934	2.0–2.5
6	—	—	1,118	2.5–5.5

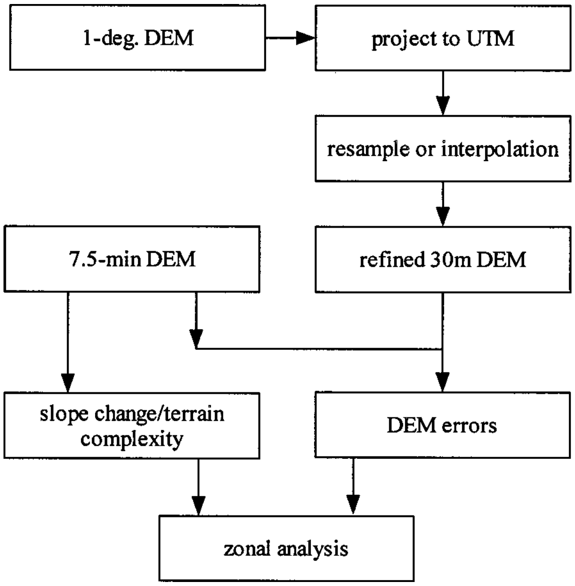
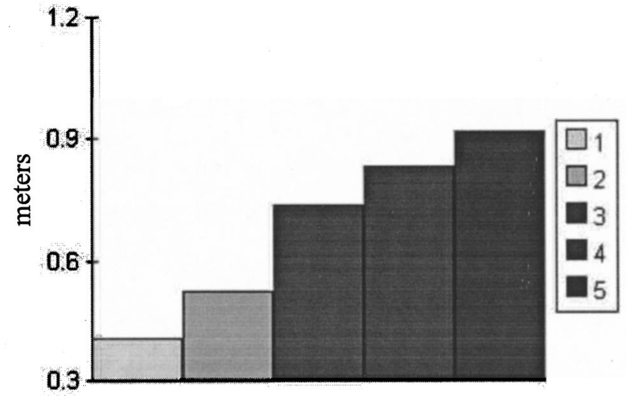
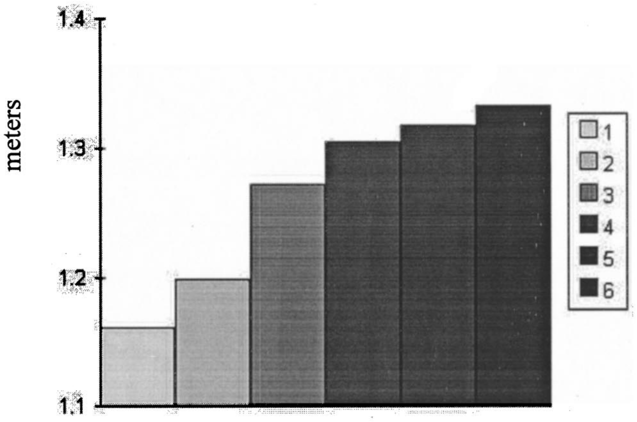


Fig. 2. Flowchart of the study approach

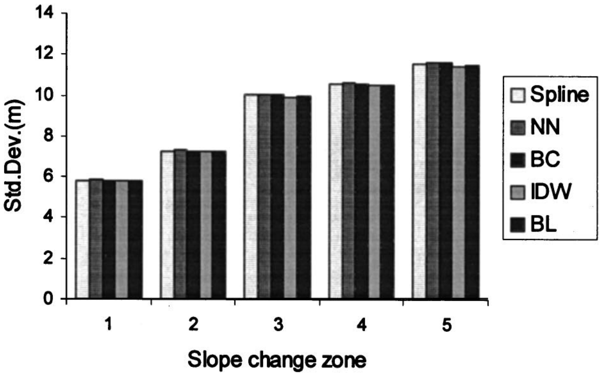


a. Slope change zone, flat area

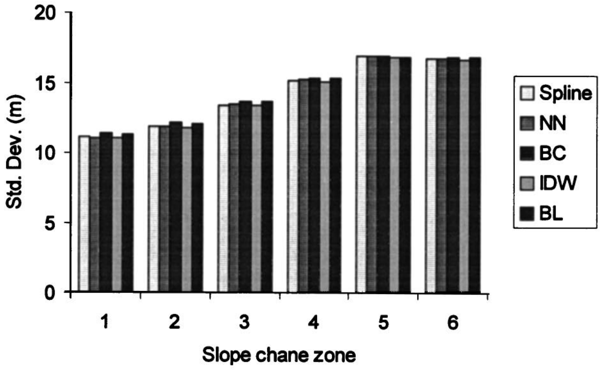


b. Slope change zone, rough area

Fig. 3. Standard deviation between the IDW and spline derived DEMs

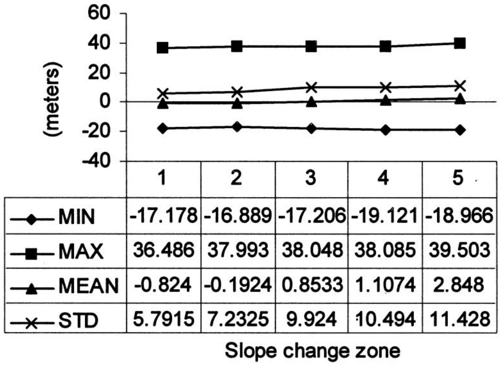


a. Flat area



b. Rough area

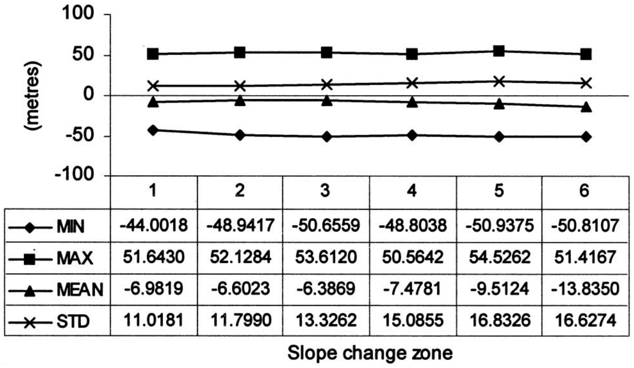
Fig. 4. Standard deviation of the refined 1-degree DEM comparing to the 7.5-min DEM



	1	2	3	4	5
◆ MIN	-17.178	-16.889	-17.206	-19.121	-18.966
■ MAX	36.486	37.993	38.048	38.085	39.503
▲ MEAN	-0.824	-0.1924	0.8533	1.1074	2.848
× STD	5.7915	7.2325	9.924	10.494	11.428

Slope change zone

a. Flat area



	1	2	3	4	5	6
◆ MIN	-44.0018	-48.9417	-50.6559	-48.8038	-50.9375	-50.8107
■ MAX	51.6430	52.1284	53.6120	50.5642	54.5262	51.4167
▲ MEAN	-6.9819	-6.6023	-6.3869	-7.4781	-9.5124	-13.8350
× STD	11.0181	11.7990	13.3262	15.0855	16.8326	16.6274

Slope change zone

b. Rough area

Fig. 5. Statistics of the IDW interpolated DEM

These coefficients are calculated with the elevations in a 3×3 window at the DEM cell to be studied. The slope change or curvature Δs is defined as

$$\Delta s = \left(\frac{\partial^2 Z}{\partial X^2} + \frac{\partial^2 Z}{\partial Y^2} \right) \tag{2}$$

When the quadratic expression Eq. (1) is used to approximate the local topography, the slope change in Eq. (2) can then be calculated with the following equation:

$$\Delta s = 2(d+e) \tag{3}$$

For the convenience of this analysis, the slope change takes the unit of degrees per hundred meters.

One flat area in northern Indiana and one rough area in the southern part of the state, each covering about 6×8 (48 km^2), are selected for this study. Fig. 1 shows the elevation, slope, and slope change obtained from the 7.5-min DEM for the two test areas. The original spatial resolution of the 1-degree DEM and 7.5-min DEM are 3 arc seconds and 30 m, respectively. For comparison and analysis purposes the 1-degree DEM is projected from the geographic coordinate system to UTM (Universal Transverse Mercator) projection (zone 16) at a spatial resolution of 82 m, so that it has the same spatial reference as the 7.5-min DEM.

The 1-degree DEM needs to be refined to a 30-m spatial resolution to be compared to the 7.5-min DEM. This can be done by either resampling or interpolation. Both methods are implemented in this study. Common resampling methods used are nearest neighbor (NN), bilinear resampling (BL), and bicubic resampling (BC). Two interpolation methods, the inverse distance weighting (IDW) and spline function with both regular and tension constraints (Mitasova and Hofierka, 1993) are used for the interpolation. Twelve nearest neighboring points are selected for the interpolation calculation. With these methods, the (projected) 1-degree DEM is refined from an 82 m to a 30 m spatial resolution DEM, which is then compared with the 7.5-min DEM. Because the 7.5-min DEM has a nominal elevation standard deviation of 7.5 m, it is used as a ground truth to evaluate the 1-degree DEM that has a nominal elevation standard deviation of 30 m. The study will then analyze the differences of those two DEMs, i.e., the elevation errors of the 1-degree DEM or its derivatives relative to the 7.5-min DEM.

The DEM errors are studied in terms of refinement methods (resampling methods and interpolation methods) and terrain complexity characterized by the slope change. To facilitate the study, a GIS analysis approach called zonal analysis is utilized. First, the slope changes are calculated using Eqs. (1)–(3) and then they are classified into five or six classes, respectively, for flat and rough areas. All the DEM cells whose slope changes are within a certain range, as defined in Table 1, will form a zone. Note that each zone may contain a great number of regions that have the same slope

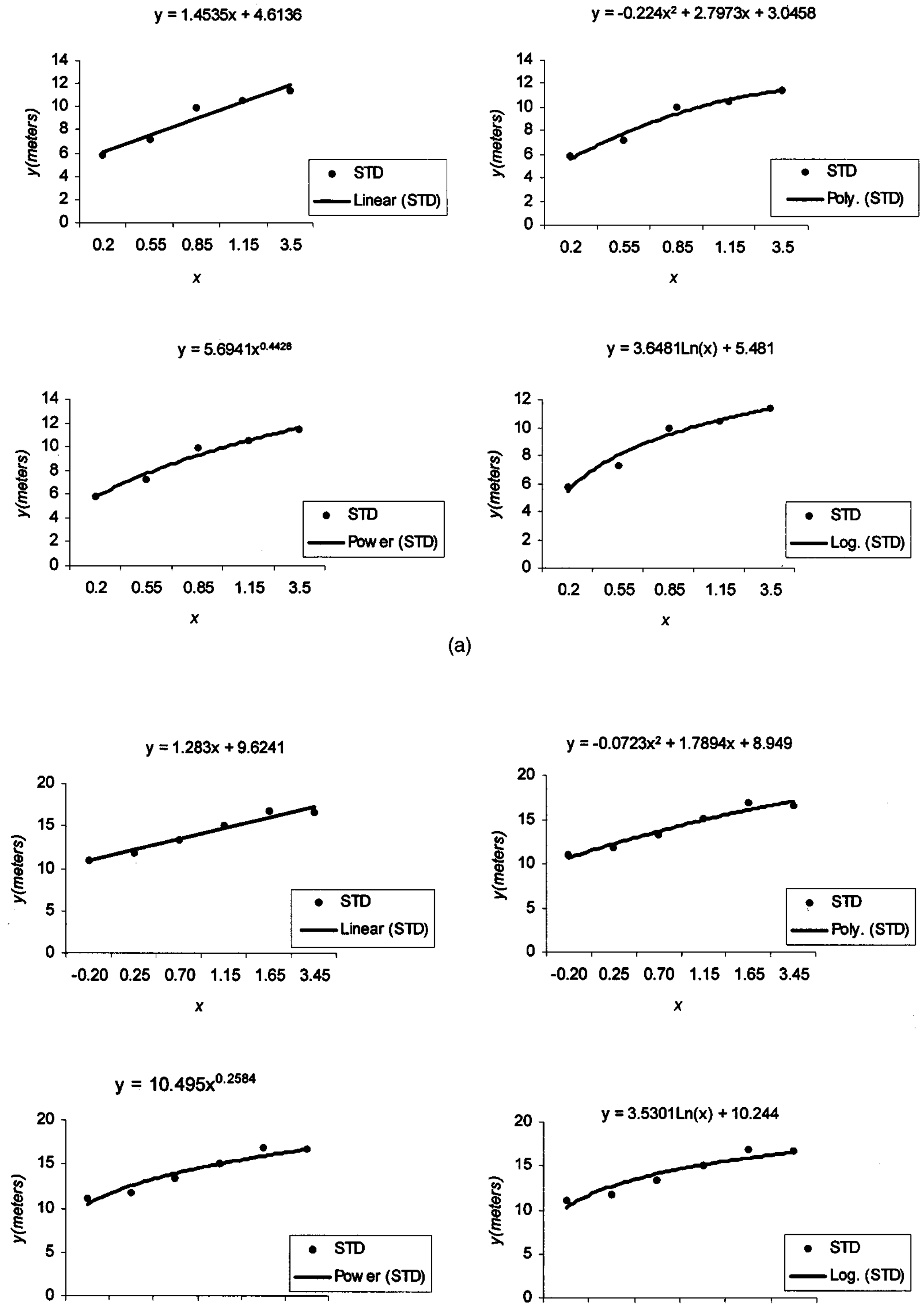


Fig. 6. (a) Standard deviation trend of the 1-degree DEM, flat area (*y*, standard deviation; *x*, slope change); (b) standard deviation trend of the 1-degree DEM, rough area (*y*, standard deviation; *x*, slope change)

change range and may not be adjacent. The statistical quantities such as the minimum, maximum, mean, and standard deviation of the DEM errors are then calculated for each zone. These zone-derived characteristics will be used for comparison, analysis, and trend estimation. Fig. 2 summarizes this approach with a flowchart.

Results and Analyses

Results from different resampling and interpolation methods are compared first. Fig. 3 shows the distribution of standard deviation versus slope change zones for the differences between the IDW and spline derived DEMs. It can be seen that the maximum variation between different interpolation methods is only within 1.0 and 1.2 m for flat and rough areas, respectively. Fig. 4 further presents the standard deviations of the DEM errors relative to the 7.5-min DEM obtained using different resampling and interpolation methods. As shown in Fig. 4, for each slope change zone the differences between different processing methods are negligible when compared to the elevation errors relative to the 7.5-min DEM. All this indicates that the processing methods in general do not cause significant differences in refining the spatial resolution for a given DEM, such as in this study where the 82-m spatial resolution DEM is processed to a 30-m spatial resolution DEM. Therefore, the DEM errors observed are mainly caused by the errors in the original 1-degree DEM itself, rather than by errors introduced in the resampling or interpolation processing. As different processing methods yield almost the same results statistically, the following analyses will only be made on the results obtained from the IDW interpolation, and they should apply to results obtained from other interpolation methods as well.

In order to study the detailed characteristics of the DEM errors, Fig. 5 illustrates the statistical quantities including minimum, maximum, mean, and standard deviation of the IDW interpolation results for both flat and rough areas. It is shown that all the errors in the rough area are larger in magnitude than the corresponding ones in the flat area, which validates the general understanding that the collection of DEM in rough areas will in general not generate results as good as in flat areas. This also shows that the two DEMs differ more in rough areas than in flat areas. Also, it is interesting to observe that the minimum and maximum errors for either flat or rough areas remain rather unchanged in different slope change zones. That means that those extreme errors may occur in all types of relief as a behavior independent of the terrain complexity. Also, it is useful to note that the 1-degree DEM may differ from the 7.5-min DEM with a maximum error up to $\sim 36-50$ m in almost all slope change zones. This fact reveals that the largest errors of the 1-degree DEM relative to the 7.5-min DEM can occur in all terrain relief types in the data sets. In contrast to other statistical quantities, the standard deviation in Fig. 5 shows a trend of steady increase as the terrain slope change increases, which will be addressed later.

In order to study the quantitative relationship between DEM accuracy and slope change, the writers conducted a trend analysis on the results obtained with the IDW interpolation. Quadratic, power, logarithmic, and linear functions are used to approximate the standard deviation shown in Fig. 5. Fig. 6 illustrates the regression results for flat and rough areas, where the dots are the calculated standard deviations from the DEM interpolation, and the curve is obtained from the regression calculation. These trend curves clearly show that the standard deviation of DEM errors increases as the slope change increases. It is also shown that, although the 1-degree DEM has smaller errors in the flat area, they increase in a steeper manner than the errors in the rough area. An examination of the fit between the curve and the dots shows that the accuracy of the 1-degree DEM deteriorates in a nonlinear manner as the terrain slope change increases. As shown in Fig. 6, however, the trend of the standard deviation in terms of terrain complexity can be approximated to a large extent by a linear function of the slope change.

Conclusions

The accuracy of the 1-degree DEM is studied by using the 7.5-min DEM as a reference. The terrain complexity is quantitatively described by its slope change or curvature. It is shown that the accuracy of the 1-degree DEM as well as its resultant DEM at a finer spatial resolution are dependent on the slope change. The standard deviation of the DEM's errors increases as the terrain slope change increases and can be approximated to a large extent with a linear function of the slope change. Although the standard deviations of the 1-degree DEM over the two test areas range from $\sigma = 11$ to 16 m, their maximum errors can reach as large as $\sim 36-50$ m (about 3σ) and occur at all slope change zones. DEM providers and users should realize both this dependency and independency on terrain complexity in the 1-degree DEM. This study shows that the zonal analysis in GIS is a useful and convenient tool to study DEM accuracy in terms of topographic complexity. Although this approach is applied for studying the 1-degree DEM, it can also be used for other similar studies.

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