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Simulation on slope uncertainty derived from DEMs at different resolution levels: a case study in the Loess Plateau

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Slope is one of the crucial terrain variables in spatial analysis and land use planning, especially in the Loess Plateau area of China which is suffering from serious soil erosion. DEM based slope extracting method has been widely accepted and applied in practice. However slope accuracy derived from this method usually does not match with its popularity. A quantitative simulation to slope data uncertainty is important not only theoretically but also necessarily to applications. This paper focuses on how resolution and terrain complexity impact on the accuracy of mean slope extracted from DEMs of different resolutions in the Loess Plateau of China. Six typical geomorphologic areas are selected as test areas, representing different terrain types from smooth to rough. Their DEMs are produced from digitizing contours of 1:10,000 scale topographic maps. Field survey results show that 5 m should be the most suitable grid size for representing slope in the Loess Plateau area. Comparative and math-simulation methodology was employed for data processing and analysis. A linear correlativity between mean slope and DEM resolution was found at all test areas, but their regression coefficients related closely with the terrain complexity of the test areas. If taking stream channel density to represent terrain complexity, mean slope error could be regressed against DEM resolution (X) and stream channel density (S) at 8 resolution levels and expressed as (0.0015S2+0.031S-0.0325)X-0.0045S2-0.155S+0.1625, with a R2 value of over 0.98. Practical tests also show an effective result of this model in applications. The new development methodology applied in this study should be helpful to similar researches in spatial data uncertainty investigation.

Simulation on slope uncertainty derived from DEMs at different resolution levels: a case study in the Loess Plateau TANG Guoan1,2, ZHAO Mudan1,3, LI Tianwen1, LIU Yongmei1,3, ZHANG Ting1 (1. Department of Urban and Resource Science, Northwest University, Xi´an 710069, China; 2. National Laboratory for Information Engineering in Survey, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China; 3. Institute of Soil and Water Conservation, CAS and Ministry of Water Resources, Yangling 712100, China) 1 Introduction Slope is a key topographic variable that exerts great impact on the degree of soil erosion and land use types. Mean slope is commonly accepted as the best factor revealing the relief roughness of a given area. At present, DEM based spatial analysis has been commonly accepted as a convenient and effective approach in deriving topographic variables. DEMs of different spatial scales were constructed, serving as a good basis for further terrain analysis. However, there is an obvious accuracy difference in extracting slope gradient from DEMs of different scales and resolutions (grid size). Besides this, other factors, i.e., the arithmetic for extracting slope and the surface complexity characteristics, all contribute to the complexity and the uncertainty of slope derived from DEMs. The accuracy of slope gradient extracted from DEMs is affected by a variety of factors, including the quality of source data, the algorithm for calculating gradient, grid size and terrain complexity. Hodgson (1995) compared the accuracy and applicability of the deriving algorithms (Ahmadzadeh and Petrou, 2001). Chang (1991), Gao (1997) and Tang (2001) revealed a variation tendency of slope accuracy along with grid size. A lot of recent researches are concerning about the propagation of slope error in terrain analysis. Comparatively speaking, less work has been done in investigation on how resolution and terrain complexity impact the accuracy of mean slope derived, as well as the spatial distribution pattern of the errors, which is of critical significance both in theory and applications. This paper focuses mainly on the accuracy of mean slope derived in the Loess Plateau area of China. A comparative and math-simulation methodology was employed in this research to investigate the impact of resolution and terra in roughness on the accuracy of mean slope derived from grid DEMs. Six areas from different terrain types were taken as test areas in this study. Aided by the experimental results from both field survey and math-simulation, an empirical model of mean slope error was constructed, which can effectively reveal the mean slope error impacted from DEM resolution and terrain complexity. This result is significant not only in the theory, but also in the applications of many fields, especially in building up a standard for spatial data application in the Loess Plateau area, which is a key developing area in western China. 2 Research basis 2.1 Test area To represent the terrain types in loess yuan, loess low hill, loess liang hill, loess mao hill and loess gully hill respectively, six 5 km × 5 km areas with different relief complexities of the Loess Plateau are selected as test areas. Table 1 shows their major topographic characteristics. 2.2 Original data and their accuracy Original DEMs all have a 5 m spatial resolution, so as to give six 2000 cells subsets. They are derived by means of digitized contour of 1:10,000 scale topographic maps. A series of experiments were done to investigate the accuracy of original DEMs. Besides a careful comparison of the difference between original contours and DEM derived ones, more work is done to measure and calculate the elevation difference between the benchmarks available on the topographic map and the corresponding elevation values of the DEMs (Table 2). This experiment takes 1828 random sampling points in field from the 6 test areas and measures their slope gradient and geographical coordinates. Then, a comparison with slope extracted from DEMs shows that the error could be kept at rather a small level, if the DEM resolution is lower than 5 m (Table 3). Hence, in this study, the slope value from 5 m resolution DEM was taken as criteria to test the slope accuracy from other resolution DEMs. 3 Experimental result and discussion 3.1 Resolution, terrain and slope spectrum Slope composition pattern in an equal-interval classification can be defined as slope spectrum. A comparison of slope spectrums at different terrain test areas reveals the impact of resolution and terrain on slope accuracy. Resolution affects gradient in that slope with an intermediate gradient becoming predominant, whereas the extremely large gradients lose their members as resolution decreases from 5 m to 65 m. The slope spectrums at the three terrain types take a different distribution pattern with a five-degree equal-interval gradient classification. Figure 3 shows the slope spectrum takes almost similar composition patterns at different resolution levels in loess yuan. However, in loess hilly-gully area, although all the slope spectrums take a bell-shaped distribution with gradient, their peaks move toward lower class with the decrease of resolution, which reveals smooth slope gets predominant as extremely large gradient gets lost. Figure 4 gives a series of slope maps from DEMs at different resolution levels, which show obviously that steep slope grids lost their value along with the decrease of resolution. 3.2 Modeling mean slope error ArcView spatial analysis function was employed as a basic platform for deriving slope gradient. SPSS was used for statistics and data processing. Mean slope from different resolution levels could be extracted. The values of mean slope are plotted against resolution to investigate their relation (Figure 3). These plots show a linear decrease with the increase of grid size from 5 m to 75 m. The finer the DEM resolution, the more accurate the terrain is represented. Such a finding result from a basic fact that the approximation of a continuous terrain with a grid based DEM is more accurate if the grid cell has a smaller size. The finer the resolution, the better the elevation of a cell approaches within the terrain it covers. In addition, a finer resolution means that the DEM cell size is smaller and more elevations are sampled. A larger sample size undoubtedly captures the terrain better. Figure 5 shows that these error statistics all appear to have a negative linear correlation with DEM resolution. To explore how DEM resolution affects mean slope extracted quantitatively, mathematical simulations are made with a series of regression analyses. Mean slope values from different resolution and terrain test areas are regressed against the resolution respectively. Figure 5 shows that all the mean slope value has a perfect linear correlation relationship with the resolution at all terrain areas. All correlation coefficients are over 0.99 and are significant at 0.01 level. Figure 5 also reveals a good explanation of how mean slope changes with the terrain complexity at a global level. First of all, the regression line for the loess hilly-gully area lies on the top and that for the loess yuan area lies at the bottom. This result indicates that mean slope is inversely associated with terrain complexity, namely a rough terrain is less accurately represented than a simple terrain at the same resolution level. In order to be represented at the same accuracy level, a rough terrain requires a finer resolution than a smooth terrain does. However, the six values are extremely close at a finer resolution (Figure 5). Their discrepancy grows increasingly wider as resolution decreases, even though all of them rise progressively. Therefore, mean slope in a rough terrain is more sensitive to the resolution reduction than those in smooth areas. Secondly, the regression equation (Figure 5) shows that the terrain complexity is obviously related to the regression coefficients. Rearranging these expressions, we can obtain a group of regression equations (Equation 1). Mean slope Y = -0.2274X + 30.518 (loess gully hill)-0.1596X + 27.456 (loess liang hill)-0.1375X + 24.515 (loess mao hill)-0.0772X + 16.407 (loess low hill)-0.0542X + 11.158 (loess yuan II)-0.0327X + 6.5795 (loess yuan I) (1) Rewriting the above equation group, we can obtain a general equation:

Y = a · X + b (2) Coefficients a and b appeared to have a liner correlation with ground surface roughness (Figures 6 and 7). A series of correlation analyses show that stream density can obtain the best correlation result. (correlation coefficient r > 0.99 with the significance at 0.01 level) Let S denote the stream density, the regression models in the figure can be rewritten as: a = -0.0015S2 - 0.031S + 0.0325 (r = 0.9999, r2 = 0.9999, p < 0.01) (3) b = -0.933S2 + 13.186S - 15.652 (r = 0.9999, r2 = 0.9994, p < 0.01) (4) substituting (3), (4) to (2), we have: Y= (-0.0015S2 - 0.031S + 0.0325)X + (-0.933S2 + 13.186S - 15.652) (5) where S and X represent stream density and resolution, respectively. If we treat the mean slope Y5 with the resolution of 5 m as true value, the mean slope error E can be derived by calculating the difference between Y5 and Y. Then we have: E = Y5 - Y = (0.0015S2 + 0.031S - 0.0325)X - 0.0045S2 - 0.155S + 0.1625 (6) This mean slope error model should be significant in assessing slope accuracy derived. Besides this, this model can also be used to determine the DEM resolution appropriate to the slope accuracy requirement of a particular user. 3.3 Testing the applicability of the error model To verify the correctness and applicability of the error model, a test experiment was done. Five different terrain complexity tests were made to verify the correctness of the error model. Table 5 shows this model can effectively correct mean slope error resulting in northern Shaanxi Loess Plateau area. 4 Conclusion Both field and statistics show 5 m is a suitable resolution value representing slope in the Loess Plateau area. There was a statistically significant correlation between mean slope derived from grid based DEM with grid size as well as stream network density. Mean slope derived decreases linearly with its spatial resolutions ranging from 5 m to 75 m. The accuracy representing a slope with gridded DEM becomes lower and lower as the resolution decreases. The decrease in accuracy is higher at a coarse resolution but minimal at a fine resolution. The accuracy of terrain representation is also inversely correlated with terrain complexity. The slope representation accuracy is more sensitive to resolution reduction for a complexity terrain than a simple terrain. Having consistent ratios to mean slope for all the six terrain types, the density of stream channel-networks is a better indicator of the representation accuracy than other terrain variables. The relation among resolution X, terrain complexity S and the derived mean slope error E may be expressed as E = (0.0015S2 + 0.031S - 0.0325)X - 0.0045S2 - 0.155S + 0.1625. This model is verified to be of a higher correctness in northern Shaanxi Loess Plateau. This model can also be used to determine the DEM resolution appropriate to the slope accuracy requirement of a particular user.

关键词： Loess Plateau; DEM; slope; terrain

