EFFECT OF DEM ACCURACY ON WATERSHED EROSION

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ABSTRACT: Our recent study of surface erosion at Shihmen reservoir watershed in Taiwan indicated that the Slope Length Factor (L) and the Steepness Factor (S) might have greater influence on erosion than the previously thought Vegetation Factor (C). Since both L and S were calculated from Digital Elevation Models (DEMs), it was important to examine how the accuracy of a DEM could affect the L and S factors, which in turn could affect the erosion amount. In order to achieve this objective, we applied uniform random errors in the range of -20 m to +20 m to the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) before calculating L, S, and surface soil erosion. Keeping all other factors constant, we repeated the process 30 times to achieve statistical significance. The results showed that the variation of erosion due to changing DEMs was between -15.01% and +2.19%.

1. INTRODUCTION AND MOTIVATION

Shihmen reservoir is one of the most important reservoirs in Taiwan. The effective storage volume of the reservoir is 207,000,000 m^3(Northern Region Water Resources Office, 2015). In addition to irrigation, power generation, and flood control, Shihmen reservoir also provides industrial and municipal water supply to several highly populated areas in northern Taiwan. Therefore, it is important to limit sediment input into the reservoir and to extend the design life of the reservoir (Jhan et al., 2013). Previously Jhan (2014) computed the amount of erosion in the Shihmen reservoir watershed. Then, Yang (2016) showed that Slope Length Factor (L) and Steepness Factor (S) had a greater influence on erosion than Vegetation Factor (C). The current study is based on the work of Jhan (2014) and Yang (2016) to further examine the effect of DEM (Digital Elevation Model) on the amounts of erosion.

2. RESEARCH MATERIAL

In order to compute surface soil erosion, a GIS system is needed. We adapted and expanded the system created by Jhan (2014) and improved by Yang (2016) for the current study. The GIS system of Jhan (2014) had R_m, K_m, C, and P map layers. In this study, we re-created L and S layers for each DEM.

2.1 Universal Soil Loss Equation (USLE)

The model used in this study is the Universal Soil Loss Equation (USLE), which is the same as that of Jhan (2014) and Yang (2016). USLE is also the only model used in the Handbook of Soil and Water Conservation of Taiwan (Soil and Water Conservation Bureau, 2005). The USLE equation is as follows (Gray and Sotir, 1996; Wu et al., 1996):

$$A_m = R_m \times K_m \times L \times S \times C \times P \tag{1}$$

where

- A_m: computed soil loss per unit area for a given time interval (tonne/hectare/year)
- R_m: rainfall factor (10^6joule-mm/hectare/hour/year)
- K_m: soil erodibility factor (tonne-hour/10^6joule/mm)
- L: slope length factor
- S: steepness factor
- C: vegetation factor
- P: erosion control practice factor

GIS map layers of R_m, K_m, L, S, C, and P factors were needed for the calculation. Among them, R_m and K_m were from various published literature. The C factor was derived from the correlation table between land use and C factor (Wu et al., 1996), and the land use data was collected by the National Land Surveying and Mapping Center (2012). The P factor was set to 1 for a conservative estimation of soil loss. These four factors (R_m, K_m, C, and P) were fixed in this study to examine the effect of DEM on L and S factors, which in turn affected the amounts of erosion.

2.2 ASTER GDEM

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was generated using stereo-pair images collected by Terra satellite, and was released jointly by METI of Japan and NASA of the United States, free of charge (Jet Propulsion Laboratory, 2004). In this study, GDEM was downloaded (resolution 30 m, V1) and used to compute the Slope Length Factor (L) and the Steepness Factor (S) within Shihmen reservoir watershed. Because the ASTER GDEM had a ground resolution of 30 m, the entire watershed was divided into 30 m by 30 m cells accordingly. The map of the ASTER GDEM of Shihmen reservoir watershed is shown in Figure 1.

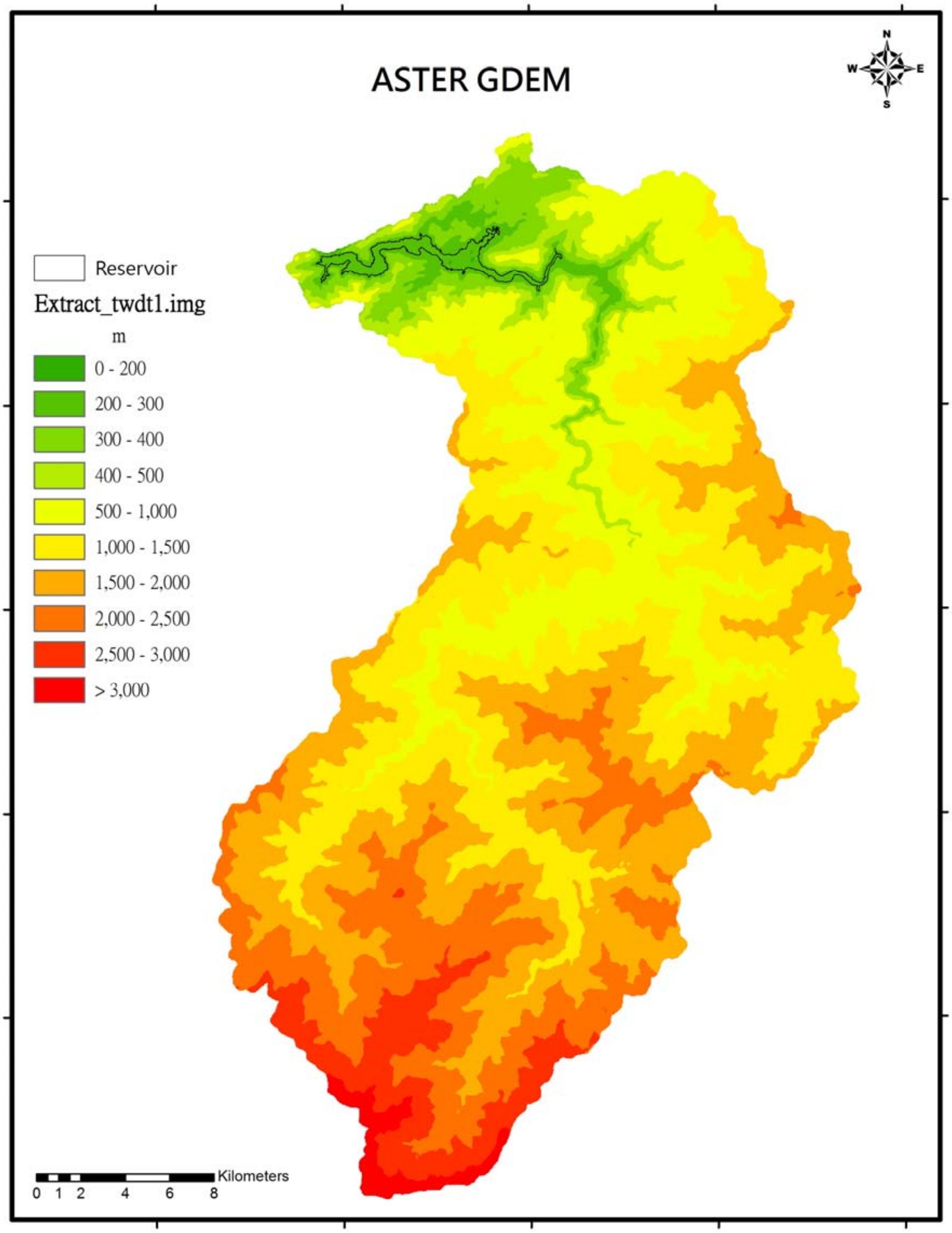


Figure 1 The ASTER GDEM of Shihmen reservoir watershed

3. RESEARCH METHOD

The ASTER GDEM covers the entire Earth between 83°N and 83°S and is freely available to researchers (GISAT, 2016). However, because of its small base-height ratio, the vertical accuracy was estimated to be 20 m (at 95% confidence). In order to see the effect of ASTER GDEM on erosion estimation, we designed an experiment to apply uniform random errors between −20 m and +20 m to ASTER GDEM, and to compute the corresponding amount of soil erosion. The automation script developed by Jhan et al. (2013) was modified to facilitate the processing of data. We first tried the built-in random number generation function of ArcGIS, but it consistently generated DEMs that had lower than the expected average elevations (-6 m). Therefore, we decided to export the original DEM to a text file, and wrote a C++ program to apply random errors between −20 and +20 m to individual values of the DEM. The new DEM was then imported back into ArcGIS to calculate erosion. The process was repeated 30 times to be statistically significant.

4. RESULTS

The results of 30 simulations (generating 30 new DEMs) are shown in the following sections.

4.1 Elevations of Simulated DEMs

Figure 2 shows a small area of Figure 1 near the reservoir. A cross-section was cut (shown in red line) to reveal the ground terrain. Figures 3 and 4 are the profiles of the same cross-section, one before the application of the random errors and the other after their application. It can be clearly seen that the original terrain (Figure 3) is smooth, and the new terrain is rugged (Figure 4). The minimum, maximum, and average elevations of the original DEM and the 30 simulated DEMs are summarized in Table 1. As can be seen from the table, the average elevations of the 30 new DEMS remained the same as that of the original DEM, but the elevations now have wider ranges.

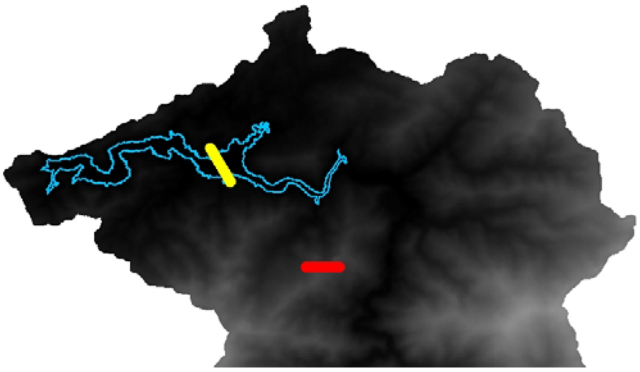


Figure 2 Location of cross-section for elevation comparison (red line)

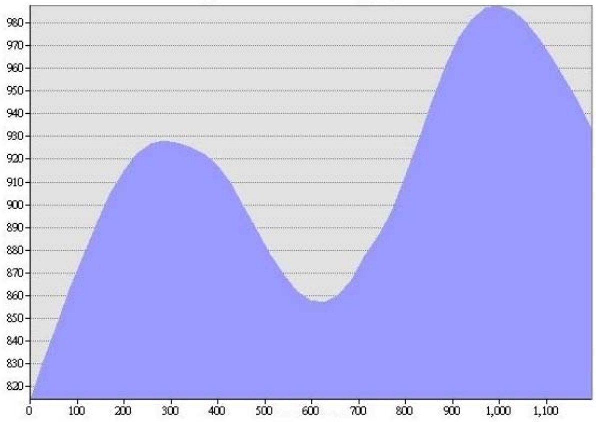


Figure 3 Cross-section of the original DEM

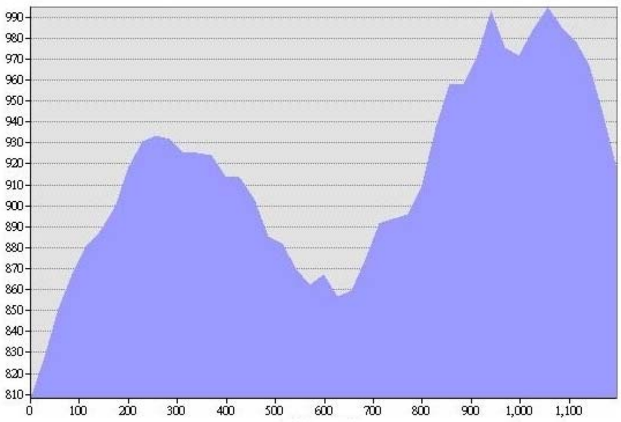


Figure 4 Cross-section of a simulated DEM (random errors added)

Table 1 Elevations of the original and 30 simulated DEMs

DEM	Max Elev. (m)	Min Elev. (m)	Average Elev. (m)
Original DEM	3,459	159	1429.650
Simulation #1	3,477	147	1429.137
Simulation #2	3,475	148	1429.160
Simulation #3	3,472	145	1429.146
Simulation #4	3,471	139	1429.145
Simulation #5	3,473	140	1429.164
Simulation #6	3,477	141	1429.138
Simulation #7	3,475	142	1429.144
Simulation #8	3,478	162	1429.153
Simulation #9	3,472	140	1429.143
Simulation #10	3,468	149	1429.170
Simulation #11	3,474	152	1429.157
Simulation #12	3,472	151	1429.147
Simulation #13	3,466	144	1429.159
Simulation #14	3,476	147	1429.169
Simulation #15	3,474	148	1429.162
Simulation #16	3,473	145	1429.153
Simulation #17	3,476	139	1429.149
Simulation #18	3,467	153	1429.151
Simulation #19	3,476	149	1429.165
Simulation #20	3,472	140	1429.159
Simulation #21	3,469	147	1429.167
Simulation #22	3,473	140	1429.135
Simulation #23	3,478	143	1429.156
Simulation #24	3,475	154	1429.145
Simulation #25	3,475	156	1429.150
Simulation #26	3,474	151	1429.163
Simulation #27	3,474	150	1429.144
Simulation #28	3,475	151	1429.148
Simulation #29	3,469	145	1429.143
Simulation #30	3,475	140	1429.159

Table 2 shows the statistical values of the L and S factors. Table 2 shows the maximum L, minimum L, average L, maximum S, minimum S, and average S for each simulated DEM. Compared with the original DEM, we can see that on average the L factor remained the same while the S factor increased by 9.75%.

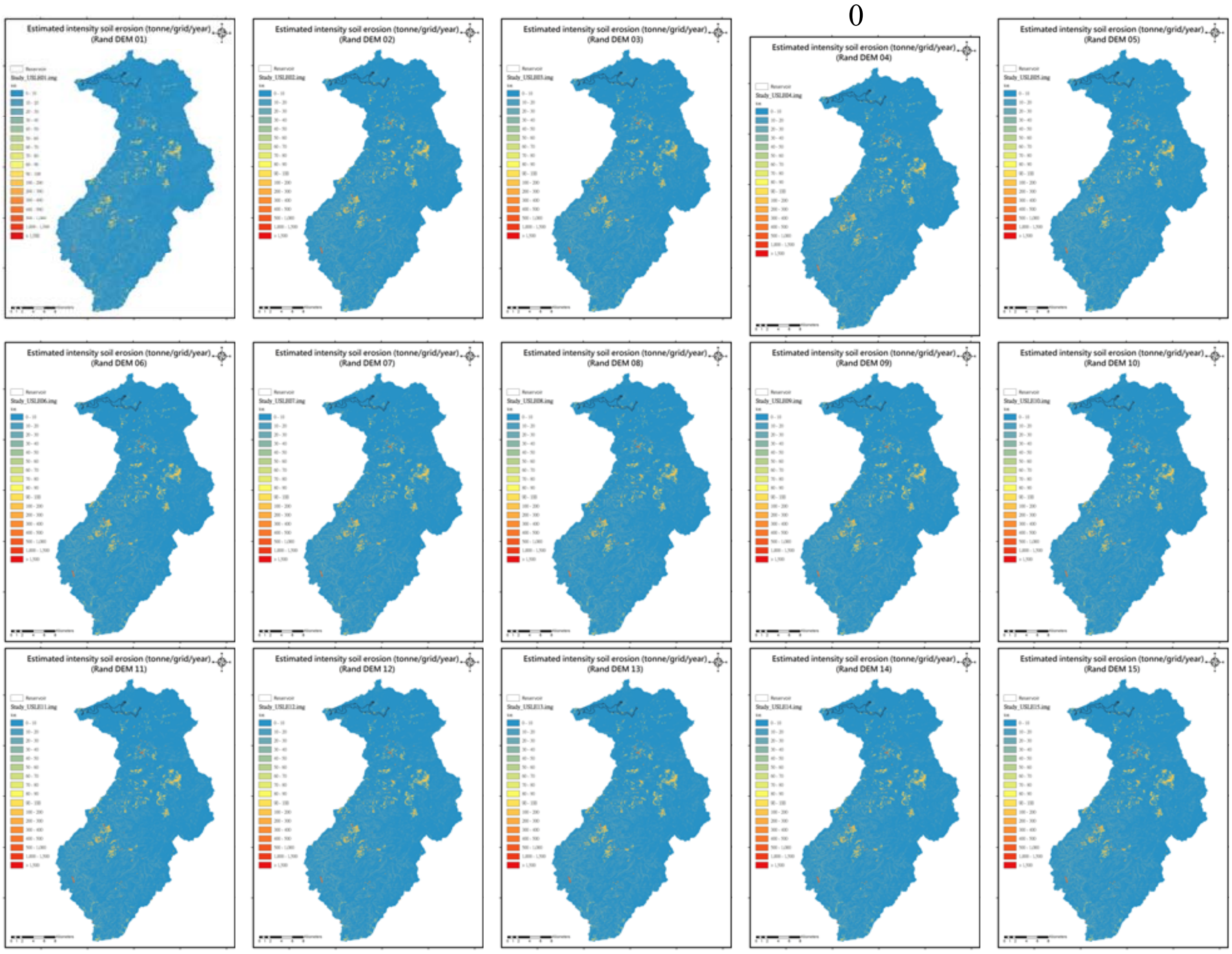
Table 2 Comparison of L and S factors between the original and 30 simulated DEMs

DEM	Max L	Min L	Average L	Max S	Min S	Average S
Original	2.302	1.063	1.351	64.255	0.065	16.497
Simulation #1	2.414	1.063	1.352	64.872	0.065	18.100
Simulation #2	2.393	1.063	1.353	64.252	0.065	18.112
Simulation #3	2.361	1.063	1.352	64.162	0.065	18.107
Simulation #4	2.351	1.063	1.353	64.639	0.065	18.111
Simulation #5	2.295	1.063	1.353	63.866	0.065	18.117
Simulation #6	2.305	1.063	1.352	63.991	0.065	18.111
Simulation #7	2.490	1.063	1.352	63.385	0.065	18.104
Simulation #8	2.342	1.063	1.352	64.623	0.065	18.098
Simulation #9	2.348	1.063	1.353	63.143	0.065	18.110
Simulation #10	2.337	1.063	1.353	63.368	0.065	18.109
Simulation #11	2.314	1.063	1.352	64.684	0.065	18.104
Simulation #12	2.392	1.063	1.352	64.385	0.065	18.106
Simulation #13	2.319	1.063	1.352	64.246	0.065	18.109
Simulation #14	2.361	1.063	1.352	63.332	0.065	18.097
Simulation #15	2.333	1.063	1.353	65.036	0.065	18.107
Simulation #16	2.338	1.063	1.353	64.409	0.065	18.108
Simulation #17	2.353	1.063	1.352	63.671	0.065	18.103

Simulation #18	2.355	1.063	1.353	64.685	0.065	18.114
Simulation #19	2.400	1.063	1.352	64.490	0.065	18.095
Simulation #20	2.505	1.063	1.352	64.381	0.065	18.116
Simulation #21	2.295	1.063	1.353	64.782	0.065	18.102
Simulation #22	2.388	1.063	1.352	64.457	0.065	18.109
Simulation #23	2.373	1.063	1.353	63.680	0.065	18.103
Simulation #24	2.304	1.063	1.353	64.852	0.065	18.102
Simulation #25	2.309	1.063	1.353	64.606	0.065	18.111
Simulation #26	2.405	1.063	1.352	63.784	0.065	18.108
Simulation #27	2.326	1.063	1.352	64.193	0.065	18.099
Simulation #28	2.366	1.063	1.352	64.229	0.065	18.107
Simulation #29	2.342	1.063	1.352	64.976	0.065	18.103
Simulation #30	2.311	1.063	1.353	63.989	0.065	18.109
Average of 30 DEMs	2.358	1.063	1.352	64.239	0.065	18.106
difference	0.056 (2.43%)	0	0.001 (0.07%)	0.016 (0.02%)	0	1.609 (9.75%)

4.2 Erosion of Simulated DEMs

After the DEMs were generated and the L, S factors were computed, we then used them to compute the amounts of surface soil erosion in Shihmen reservoir watershed. The distributions of soil erosion were plotted as theme maps. These 30 maps are shown together in Figure 5. It can be observed that these theme maps were highly similar. However, subtle differences did exist. This is demonstrated in Table 3, where the total amounts of soil erosion and average amounts of soil erosion (per cell) were tabulated. Note that the cell size was 30 m by 30 m (as described before).



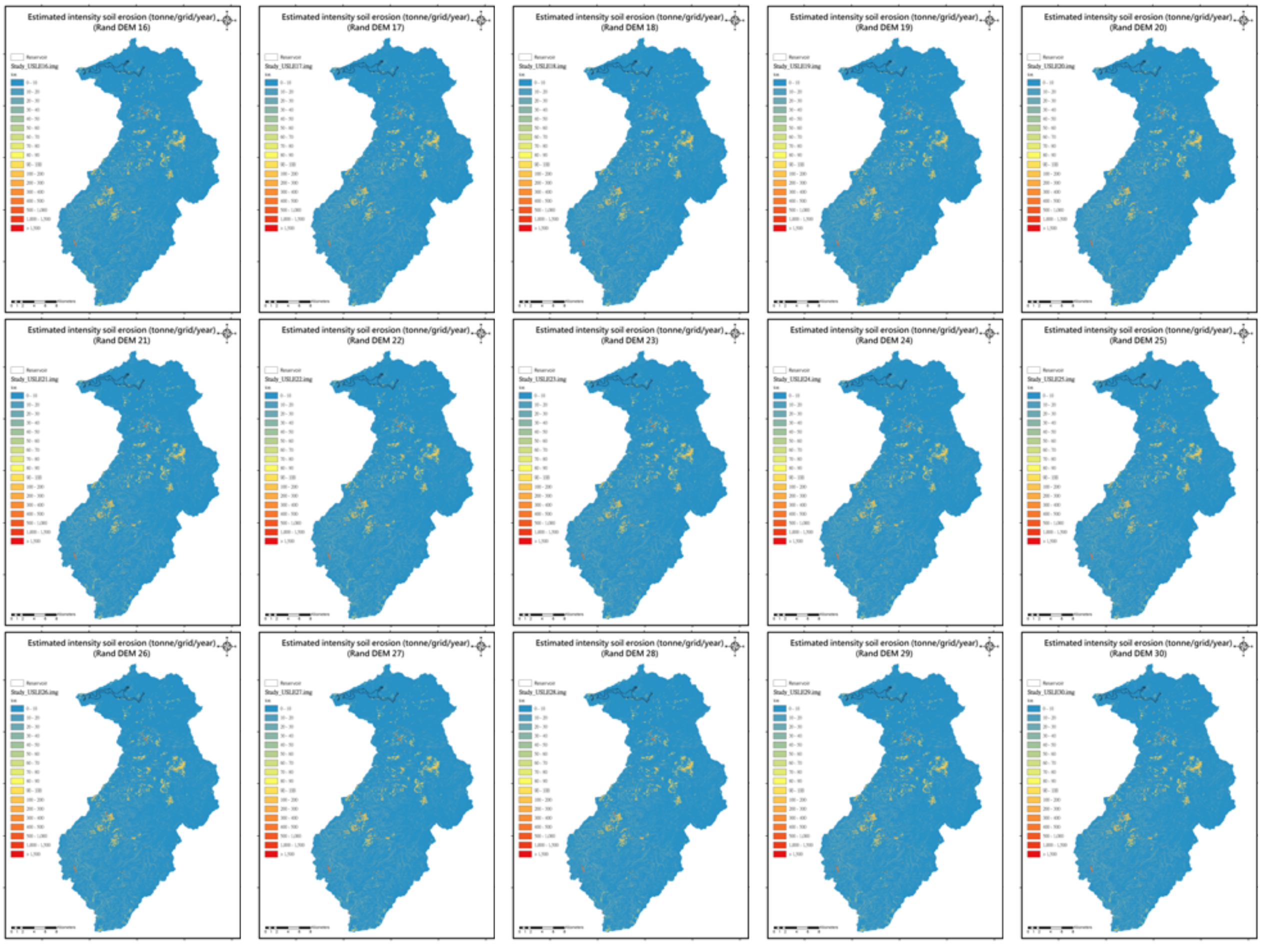


Figure 5 Soil erosion maps of 30 simulated DEMs of Shihmen Reservoir watershed

Table 3 Comparison of erosion amounts of the original and 30 simulated DEMs

DEM	Total soil erosion (ton/year)	Average soil erosion (ton/cell/year)
Original DEM	5,556,641	6.584
Simulation #1	5,276,505	6.252
Simulation #2	5,572,153	6.603
Simulation #3	5,331,461	6.317
Simulation #4	4,825,711	5.712
Simulation #5	5,573,234	6.604
Simulation #6	4,831,753	5.725
Simulation #7	5,240,677	6.210
Simulation #8	5,496,279	6.513
Simulation #9	5,035,282	5.966
Simulation #10	5,624,340	6.664
Simulation #11	5,436,499	6.442
Simulation #12	5,100,656	6.044
Simulation #13	5,174,933	6.132
Simulation #14	5,525,106	6.547
Simulation #15	4,722,524	5.596
Simulation #16	5,258,193	6.231
Simulation #17	5,446,840	6.454
Simulation #18	5,204,618	6.167
Simulation #19	5,216,895	6.182
Simulation #20	5,388,224	6.385
Simulation #21	5,678,098	6.728
Simulation #22	5,173,602	6.130
Simulation #23	5,277,950	6.254
Simulation #24	5,339,728	6.327

Simulation #25	5,199,660	6.161
Simulation #26	5,498,234	6.515
Simulation #27	5,420,623	6.423
Simulation #28	5,441,379	6.448
Simulation #29	5,518,392	6.539
Simulation #30	5,396,035	6.394

Table 4 shows the average elevation of the original DEM (1429.650 m) and the average of the average elevations of 30 simulated DEMs (1429.153 m). The difference was only 0.035%. This shows that we had good simulations and a good application of random errors. To see the influence of random errors on soil erosion, we computed the average of soil erosion for 30 simulations. The results are shown in Table 5. Unlike Table 4, Table 5 is a surprise. The analysis of the results show that the average amount of soil erosion for 30 simulations was 6.289 ton/cell/year, whereas the erosion of the original DEM was 6.584 ton/cell/year. There was a 4.48% reduction in soil erosion.

Table 4 Original DEM vs. the average of 30 simulated DEMs

Average elevation of the original DEM (m)	1429.650
Average of the average elevations of 30 simulated DEMs in Table 1 (m)	1429.153
Difference (m)	0.497 (0.035%)

Table 5 Comparison of erosion amounts between the original and the average of 30 simulated DEMs

DEM	Original DEM	Maximum of 30 DEMs (Table 3)	Minimum of 30 DEMs (Table 3)	Average of 30 DEMs (Table 3)
Total soil erosion (ton/year)	5,556,641	5,678,098	4,722,524	5,307,519
Average soil erosion (ton/cell/year)	6.584	6.728 (+2.19%)	5.596 (-15.01%)	6.289 (-4.48%)

5. SUMMARY AND CONCLUSION

In this study, we applied random errors of between −20 m and +20 m to the ASTER GDEM before calculating L, S, and surface soil erosion. Keeping all other factors constant, we repeated the process 30 times to achieve statistical significance. The results showed that the average erosion decreased as a result of introducing inaccuracy to the original DEM.

The difference of soil erosion due to changing DEMs was between −15.01% and +2.19%, which was not much (Table 5). However, the average erosion in the 30 simulations was not the same as that of the original DEM (as in the case of average elevations), and that caught our attention. The computation showed that the average of the 30 simulations was 6.289 ton/cell/year, representing a 4.48% reduction in the original amount of erosion. That seemed to indicate that introducing inaccuracy to DEM actually reduces erosion. There are two possible explanations for this unexpected result. First, although the average S factor increased in all 30 cases (increase of ruggedness), they could be distributed in such a way that they had little effect on the total amount of erosion, e.g., distributed on the same cells with almost zero C factors. Second, we took the output results “as is” from ArcGIS. The implementation details of ArcGIS could be causing the discrepancy from the anticipated results.

In conclusion, this study demonstrates that the effect of inaccurate DEM on soil erosion can be quantified. Random errors of known magnitude can be added to the source DEM to simulate results, and the process can be programmed and repeated enough times to achieve statistical significance. However, critical questions remain as to how to explain the observed discrepancy.

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