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Identifying and comparing relatively high soil erosion sites with four DEMs

Walter Chen[a,*], Dong-Huang Li[a], Kai-Jie Yang[a], Fuan Tsai[b], Uma Seeboonruang[c]

[a] Dept. of Civil Engineering, National Taipei University of Technology, Taipei, Taiwan, ROC
[b] Center for Space and Remote Sensing Research, National Central University, Zhongli, Taiwan, ROC
[c] Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand

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ABSTRACT

Soil loss due to sheet or rill soil erosion is a critical problem in watersheds of Taiwan. However, an order-of-magnitude discrepancy of soil loss in the literature raises many questions. In this study, we conducted a new analysis using the most recent available data and the Universal Soil Loss Equation (USLE) to compute the amounts of sheet and rill erosion of the Shihmen reservoir watershed in northern Taiwan. Using four different Digital Elevation Models (DEMs), we identified relatively high soil erosion sites and found them to be located at similar locations despite of the difference in DEM. We also determined that the average soil erosion in the Shihmen reservoir watershed is comparable to other watersheds in Asia, but higher than those of the European Union. Furthermore, soil erosion is not uniformly distributed throughout the study area. It is found that the distribution of soil erosion is highly skewed to the right (right-tailed), which means that the majority of the distribution is concentrated to the left side (many cells with low soil erosion). Based on our model, approximately 2% of the areas account for 30% of the soil erosion. In other words, a small proportion of the areas contribute to a large proportion of the total soil loss. Moreover, the DEM created from airborne LiDAR yields the highest amount of soil erosion, the two DEMs created from satellite images yield the lowest amounts of soil erosion, and the DEM created from aerial photographs yields an in-between soil erosion amount. Their vertical resolutions range from high to low. It appears that the amount of soil erosion is influenced by the vertical accuracy of DEMs. In addition to the comparison of DEMs, we demonstrated rudimentary steps to visualize areas of high soil erosion risk using freely available tool for long-term monitoring.

1. Introduction

Soil loss due to surficial soil erosion and mass movement is a global problem not just for developing countries but also for developed countries. For example, the total soil loss to the European Union is estimated to be 970 million tons annually (Panagos et al. 2015a), which is a major threat to the ecosystem, crop production, and drinking water. Soil loss mostly occurs on slopes. Soil loss due to water erosion is such a crucial problem that the European Commission's Soil Thematic Strategy has identified soil erosion as a serious issue, and has drafted plans to monitor soil erosion (Panagos et al. 2015a). A global study that includes 202 countries further asserts the importance of dealing with soil erosion worldwide, and indicates that in 2012 Africa would overtake South America to become the continent with the highest average soil erosion rate of 3.88 t/ha/yr ($\mathrm{Mg\,ha^{-1}\,yr^{-1}}$), while Asia's soil erosion rate would remain at 3.47 t/ha/yr (Borrelli et al., 2017). Because high rate of soil erosion is often associated with high annual rainfall (and intensity), places exceeding the generic tolerable soil erosion threshold of 10 t/ha/yr or hot-spot value of 20 t/ha/yr (Borrelli et al., 2017) are not uncommon in countries of Southeast Asia (such as Taiwan) where typhoons and monsoon rains are frequent.

Slope degradation is divided into two categories, surficial soil erosion and mass movement (landslides). The two types of slope degradation are analyzed differently. Among them, the physical model of surficial soil erosion is usually the Universal Soil Loss Equation (USLE), and the predictive criterion of mass movement is the Factor of Safety (FS). Compared with mass movements, where the shear strength of soil is most important, surficial soil erosion is more strongly linked to factors such as the intensity of rainfall, the erodibility of soil, land cover, and the ruggedness of terrain.

In addition to the division of surficial soil erosion and mass movement, it is important to recognize that soil loss in a watershed can be alternatively divided into four groups: (1) collapses or landslides, (2) sheet and rill erosion, (3) gully erosion, and (4) channel erosion (Ouyang and Bartholic, 1997). Collapses and landslides are equivalent to mass movement, whereas sheet and rill erosion is surficial soil

* Corresponding author at: 1 Sec 3 Chung-Hsiao E. Rd., Taipei 106, Taiwan, ROC.
E-mail addresses: waltchen@ntut.edu.tw (W. Chen), ftsai@csrsr.ncu.edu.tw (F. Tsai), kseuma@kmitl.ac.th (U. Seeboonruang).

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erosion. Notice that gully erosion and channel erosion are not included in the comparison above. Many of the past studies reviewed in the following sections fail to distinguish between the different types of soil erosion, and assume that USLE is an all-encompassing method for soil erosion. In the following, we will review studies in the Asian region first and then discuss studies done on the Shihmen reservoir watershed of Taiwan.

USLE has been used in many countries such as India (Singh and Panda, 2017), Ethiopia (Subhatu et al., 2017), China (Feng et al., 2017), Spain (Mateos et al., 2017), Poland (Nowak and Schneider, 2017), Italy (Stefano et al., 2017), and Malaysia (Roslee et al., 2017) just to name a few. Take three typical studies of soil erosion in the Asian region representing watersheds from small (52 km^2, Jain et al., 2001), medium (1556 km^2, Dabral et al., 2008), to large (3200 km^2, Schonbrodt et al., 2010) size as an example for comparison. Of the three watersheds, one is in China while the other two are in the Indian Himalayan Region, featuring some of the steepest terrain in the world. The results show that the calculated amounts of soil erosion range from 22 to 58 t/ha/year in India, and from 12 to 121 t/ha/year in China. These amounts are much higher than the average soil erosion of 2.46 t/ha/year in the European Union (Panagos et al., 2015a). There is at least one order-of-magnitude difference between Europe and Asia, which indicates that soil erosion is a much more serious issue in Asia, especially in areas with highly erodible soils and steep terrains.

In addition to the studies in the Asian region, we have also exhaustively searched and collected studies done in Taiwan on the Shihmen reservoir watershed. Table 1 summarizes these past studies. As can be seen from Table 1, these studies all used USLE as their standard model. They also divided their study areas into square cells, and used grid-wise evaluation to compute soil erosion. However, the cell sizes were different. They ranged from 5 m to 120 m. The calculated amounts of soil erosion also varied considerably, from 1 to 3,310 t/ha/year. If the weight of soil erosion is divided by bulk density (1.4 t/m^3) and area of the watershed, soil erosion can be converted to average erosion depth of the entire watershed. The value varies from 0.25 mm to 236.30 mm. A difference of more than 3000 times between the lowest and highest values can be noted, and some of the estimated soil erosion amounts are even much higher than those of Table 1. In addition, some of the soil erosion amounts even fall outside the range compiled by a global meta-study based on published data from more than 4000 sites (1–10,000 Mg/km^2, or 0.01–100 ton/ha, Garcia-Ruiz et al., 2015). It is suspected that if an error has been made, that would explain the apparent discrepancy. As a consequence, during this work we use the most recent available data in a rigorous analysis in order to find the cause for this order-of-magnitude discrepancy, and to support the findings that Taiwan has a higher soil erosion rate than other countries. Moreover, we compared the amounts of soil erosion from four different Digital Elevation Models (DEMs), and examined the influence of DEM (vertical) resolution on soil erosion estimation.

Table 1
Summary of past studies of the Shihmen reservoir watershed (order-of-magnitude discrepancy observed in the amounts of soil erosion).

Studies	Model	Cell size	Surface soil erosion (t/ha/year)	Equivalent erosion depth (mm)
Lin (2002), Lin et al. (2003), Lin et al. (2006)	USLE	40 m	25	1.82
Ou-Yang (2003)	USLE	120 m	40	2.82
Chiang et al. (2007)	USLE	40 m	3 (as low as 1 for a sub-watershed)	0.25
Wu (2007)	USLE	20 m	113	8.09
Chen et al. (2009)	USLE	20 m	3310	236.30
Chi (2010)	USLE	5 m	18	1.31
Liang et al. (2010)	USLE	5 m	83 (weighted average)	5.91
Jhan (2014)	USLE	30 m 40 m	30 m: 64 40 m: 101	30 m: 4.60 40 m: 7.19

This study is based on the following research objectives (1, 5), methods and assumptions (2, 3, and 4):

1. The intent of this work is to use the most recent available data to conduct a new analysis in order to get a better estimate of soil erosion of the Shihmen reservoir watershed. It is also critical to review the large discrepancy in the estimated amounts of soil erosion in the literature.
2. In this study, we are only concerned about the so-called non-point source soil erosion (land degradation) instead of mass movement. That is, the study is centered on calculating sheet and rill erosion with USLE, and ignores gully and channel erosion as well as collapses and landslides. (There are other researches focusing on landslides and sediment yield such as Chiang et al. (2012) and Tsai et al. (2012).)
3. RUSLE (Revised Universal Soil Loss Equation) is not used in this study due to the lack of appropriate data.
4. For the purpose of this research, we assume that the data (GIS map layers) used in this study are from the same time period, or at least have the same characteristics, as those of the same study period and therefore can be used together in the analysis.
5. The main focus of this research is to map soil erosion with USLE and identify relatively high soil erosion areas. We do not attempt to verify the absolute amounts of soil erosion with field measurements because the absolute amounts are inconsequential to our main objective of identifying "relatively" high soil erosion areas. In the process, we substitute different DEMs (the resulting topographic LS-factors having the most influence on soil erosion than any other factors according to Ostovari et al., 2017) into the model while keeping other factors unchanged in order to study the effect of the types and vertical accuracy of DEMs. The substitution of DEM also serves as a validation check of the proposed method of identifying erosion prone areas.

In short, the specific aims of this research are to study the amounts of soil erosion and their distribution in the Shihmen reservoir watershed of Taiwan, and to study the effect of DEM resolution on soil erosion. Based on these results, this study will identify areas with high Soil Erosion Risk (SER), and visualize the areas for priority conservation treatment.

2. Materials and methods

In spite of the general recognition that soil erosion is a critical problem in watersheds, evaluating the potential for soil erosion and identifying priority sites for restoration judiciously can still be a formidable task because there are different models and a large number of diverse factors to consider. In this study, we use the USLE model in order to compare with past studies that used the same method. The equation of USLE in metric units is as follows (Wischmeier and Smith, 1978; 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 (t/ha/year)
R_m: rainfall factor (MJ-mm/hectare/hour/year)
K_m: soil erodibility factor (ton-hour/MJ/mm)
L: slope length factor
S: steepness factor
C: vegetation factor
P: erosion control practice factor