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Reconstructing more than 40 years soil re-distribution in two Taiwanese watersheds

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Abstract

Taiwan is a little smaller than the Netherlands, an island surrounded by the sea and has a population of circa 23 million. Add a central range of steep mountains and it is clear that the pressure on living space and natural resources is enormous. This is exemplified by the fact that Taiwan has become one of the countries facing water shortages in the next decades. Taiwan has around 40 large reservoirs that hold around 4200 million cubic meter of all water. A recent study shows that each year, around 400 million cubic meter of silt accumulates in Taiwan's reservoirs, yet only around 10% of sediment is removed. Reservoir management aims to counter the sedimentation problem at the source namely the erosion and transport of soil material.. However, effective measures require reliable data on patterns and rates of erosion in the hinterland. For example, the effects of tropical cyclones on erosion rates of forested slope land soils are not well established. Therefore, the authors present a novel method to reconstruct more than 40 years of soil erosion and deposition within the two largest reservoir catchments in Taiwan. The method combines the ^{137}Cs isotope technique, widely used to calculate soil re-distribution rates, with a detailed representation of the watersheds in a GIS. More than 160 soil profile samples were collected in undisturbed and disturbed locations across the watersheds. Sampling was based on a priori stratification of the watersheds into landscape units. Inside each unit ^{137}Cs activity levels in multiple soil profiles were analysed and published conversion techniques were applied to compute soil re-distribution rates for each site. Statistical methods were then applied to obtain the relations between re-distribution rates and landscape units. These relations were then distributed using a GIS representation of the landscape units in each watershed. The result is a series of maps that show 40 years soil erosion across the studied watersheds as well as estimates of uncertainties. It was found that soil erosion may well account for up to a quarter of total sedimentation and forested areas account for the majority of the sediment found today in the reservoir. The absolute highest erosion rates are measured in farmland. The authors believe that the method has great potential for soil erosion mitigation programs and should become a part of standard watershed investigation procedures.

Keywords: reservoir, watershed management, ^{137}Cs, GIS

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Introduction

For people living on the island of Taiwan, with an area of approximately 36,000 square kilometers, water comes from the sky rather than from waterways shared with neighboring countries. Although Taiwan's annual rainfall of 2,500mm is about 2.6 times higher than the world average, the nation's steep topography sends 46% of that rainfall directly into the sea. A little over 24% percent of the rainfall evaporates. Of the water that remains on or in the ground, 4.2 billion cubic meters are collected in reservoirs, 7.6 billion cubic meters are diverted from rivers, and 6.3 billion cubic meters are pumped from underground. About 18.1 billion cubic meters of water is available annually, shared by a population of 23 million. 75% of all available water is used for agricultural purposes, while 16% is used by families and the remaining 9% is used by industry. However, the sources of water, its distribution and availability vary across the island because of differences in climatic conditions. In the south, 90% of the total rain falls from May to October. In northern Taiwan, 60% falls during this period, while monsoon related rains also bring rain in the short winter. So about 23% of all available water is stored in reservoirs, and is primarily used for drinking water production, however, storage volumes are shrinking annually due to siltation. According to 2003 statistics, sedimentation in the top six hydraulic dams in Taiwan are as follows: Kun-Tien Hydraulic Dam: 68%, Wu-Shan-Tou Hydraulic Dam: 50%, Bai-Ho Hydraulic Dam: 42%, Shih-Shi Hydraulic Dam: 33%, Min-Der Hydraulic Dam: 20%, Shih-Men Hydraulic Dam: 19%, Tzeng-Wen Hydraulic Dam: 18%.

The sediment decreases the storage capacity and dredging proves costly while the mostly fine sediments are of little practical or economic use. Therefore, reservoir management is now looking at ways to limit the erosion and transport of fine sediments in the upstream watershed areas. Two important sources of erosion that contribute to reservoir sedimentation are the many landslides that scar mountain sides; destroy forested hill slopes, farm lands and roads. The second, less visible since diffuse, source is soil erosion caused by the detachment of soil particles on hill slopes which are transported to streams and eventually to the reservoir during overland flow. Both landslides and soil erosion are most likely to occur during the on average three to four tropical cyclones that hit the island annually. During these events more than 1000 mm of rain may fall in some areas in just 48 hours.

The relative contributions of landslides and soil erosion to reservoir sedimentation in Taiwan are not well known. Until recently, rates and distributions of soil erosion across watersheds were based solely on empirical USLE model estimates. However, the estimates that are based on experimental fields and forested areas could not always be validated by gauging station data. A second uncertainty stems from the fact that most experimental fields are situated outside the watershed area hence they can not fully represent terrain and vegetation conditions in the study area. Also, due to practical limitations they do not record the combined effect of multi-decadal storm activity.

Our aim was therefore to independently estimate soil erosion rates and their distribution across two watersheds in Taiwan. In this paper we describe the first application of the ^{137}Cs-method to compute soil erosion rates on a watershed scale in Taiwan. The initial suggestion to apply the technique in Taiwan was first published by Lee (1999). The technique is based on the distribution of the ^{137}Cs isotope – an environmental radionuclide – present in top soil layers since the end of the 1950's as an indicator for re-distribution of soil particles. The ^{137}Cs-method has been successfully applied to map re-distribution of soils for many years (Roo, 1991; Rowan, 1995) and is applied world wide (He and Walling, 1997;IAEA, 2001). Unique of the ^{137}Cs method is the fact that one can obtain long-term (40 year) average soil erosion rates for sample sites that only require a single visit, enabling the coverage of relatively large areas, or sampling fields at a very high density. Furthermore, measuring ^{137}Cs in soil samples is long a standard procedure for radio-ecological laboratories and does not prove to be very complicated.

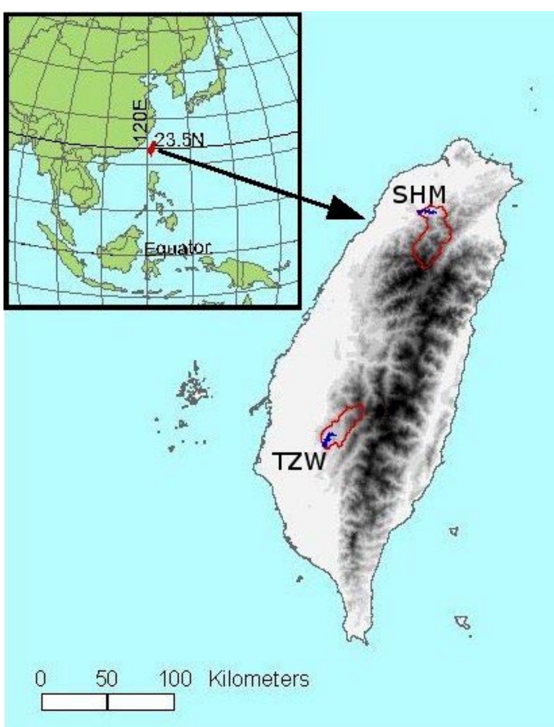

Fig. 1: Location map of the two study areas.

In this paper we present the steps that we took to calculate the long-term rates of soil erosion and their variation across two watersheds. The study areas were the Shih-Men (SHM) and Tzeng-Wen (TZW) reservoir watersheds (Figure 1). Shih-Men reservoir is the oldest and started operations in 1964, while Tzeng-Wen became operational almost a decade later in 1973. We compare our soil erosion estimate with available sedimentation records and landslide volumes and present a map of the estimated accuracy. The method as it is described below has the potential to support reservoir watershed management bureaus when planning erosion prevention strategies.

Methods

The study was divided in five stages,(Figure 2) starting from the GIS representation of the watersheds . Each step is explained in more detail below.

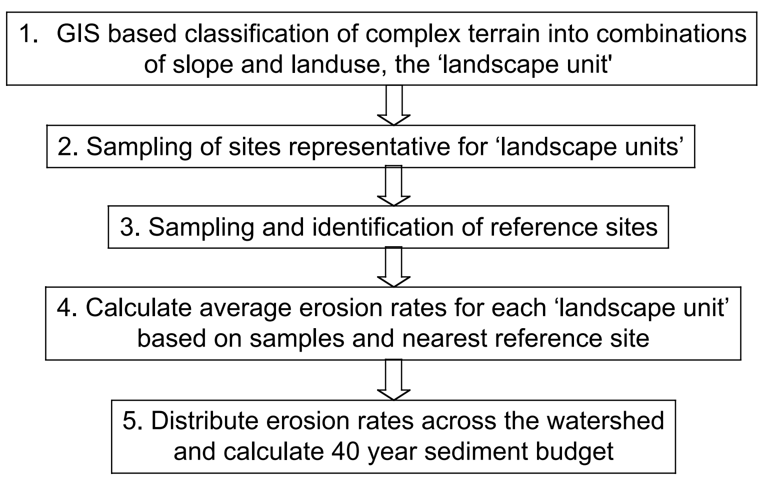

Fig. 2.: Different in the flow of work done in this study

1. GIS based classification of the watershed

The GIS data that was used to classify the watershed in landscape units was as follows:

- Land use maps of each watershed based on SPOT 4 satellite imagery from 1998, with a resolution of 20m (see Figure 3).
- Digital Terrain Models (DTM) with elevation data of the watersheds and derived slope and aspect grids with a resolution of 40 m (see Figure 4).

The distribution of land use types can be seen in Figure 3 and the relative area of each land use type is given in Tables 1 and 2. Note that Tzeng-Wen watershed has more land use types than Shih-Men. In our investigation however we re-classified the land use to three classes, namely: (i) forest; (ii) grass; and (iii) farm. Therefore, the 'farm' class in the Tzeng-Wen combines fruit farms, tea farms and 'other farms' e.g. vegetable or rice farms. Furthermore, 'landslides' and 'water bodies' were excluded from the classification since no soil samples can be taken in these classes. The slope map was also reclassified into three classes: (i) low-medium slope (0°-28°); (ii) medium-high slope (29°-56°); and (iii) high slopes (>56°). A 28° threshold was chosen since by Taiwanese law, no construction or farm land can be planned on slopes exceeding 28° (SCWB, 2003).

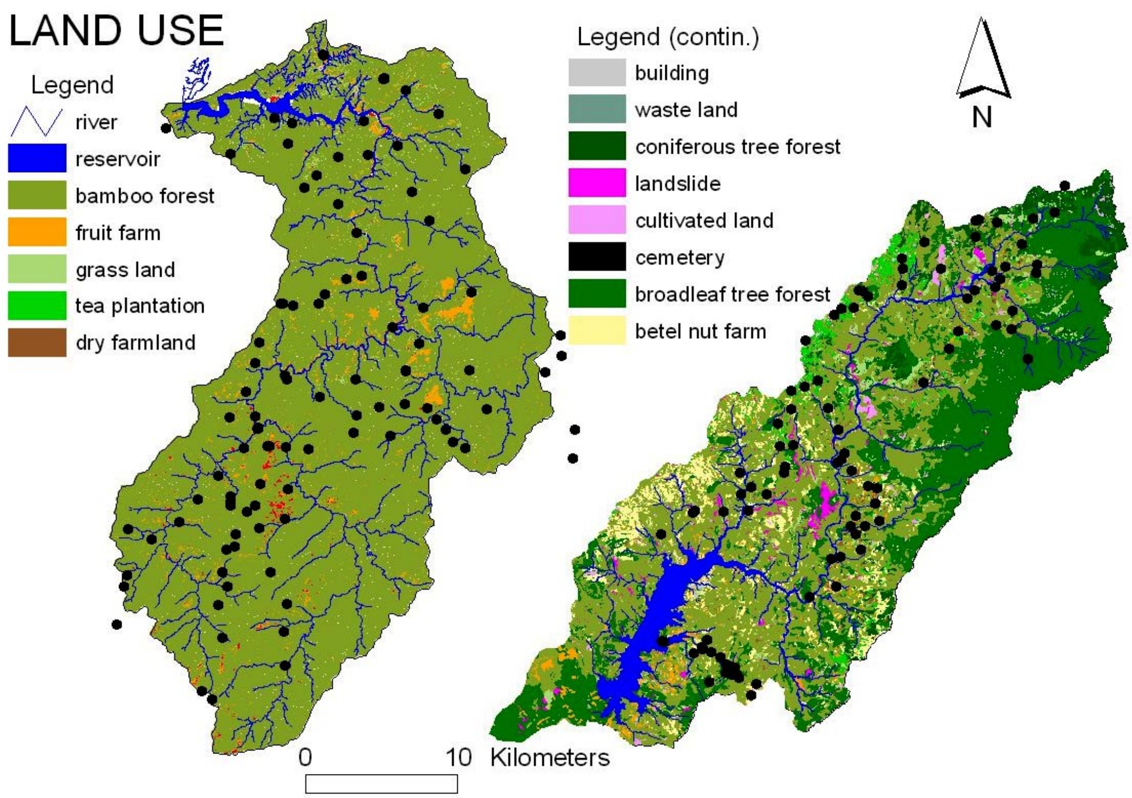

Fig. 3. Land use in Shi-Men and Tzeng-Wen watersheds, the black dots are sample sites.

In the GIS, an overlay operation was performed to combine the three land use classes and three slope classes, which in theory should result in nine landscape units. In reality not all combinations are found in the watersheds. For example, since farms are not allowed on slopes steeper than 28°, we will not find the combination of farms and high slopes.

Table 1. The land use in Shih-Men watershed (1998)

Land use	Area (ha)	%
Water bodies	751.58	1.0
Fruit farm	2304.19	3.0
Grass land	1100.41	1.5
Landslides	438.00	0.6
Forest	70967.82	93.9

Table 2. The land use in Tseng-Wen watershed (1998).

Land use	Area (ha)	%
Water bodies	2365.8	4.7
Fruit farm	3580.9	7.1
Forest	39589.4	79.0
Grass land	1777.5	3.5
Tea farm	1138.2	2.3
Landslide	681.3	1.4
Other farm	993.0	2.0

In the Figures below the distribution of slope-classes in both watersheds are shown. The Y-axis shows the number of 40x40 m grid cells. 60.5% of slopes in Shih-Men watershed are steeper than 28° versus 46.1% in Tzeng-Wen watershed.

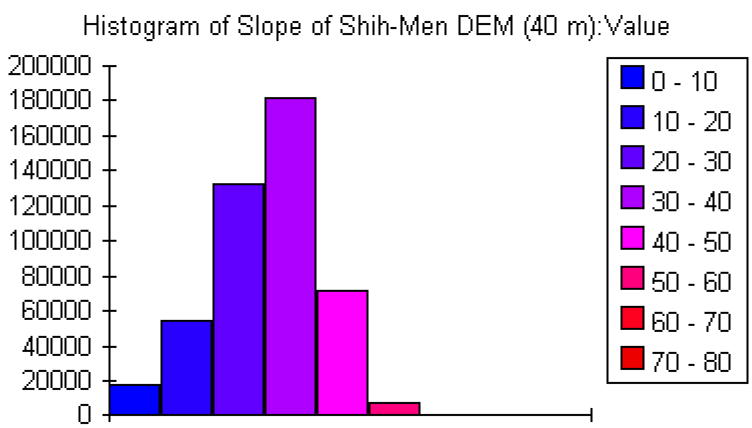

Fig. 4: Distribution of slope classes in Shih-Men watershed

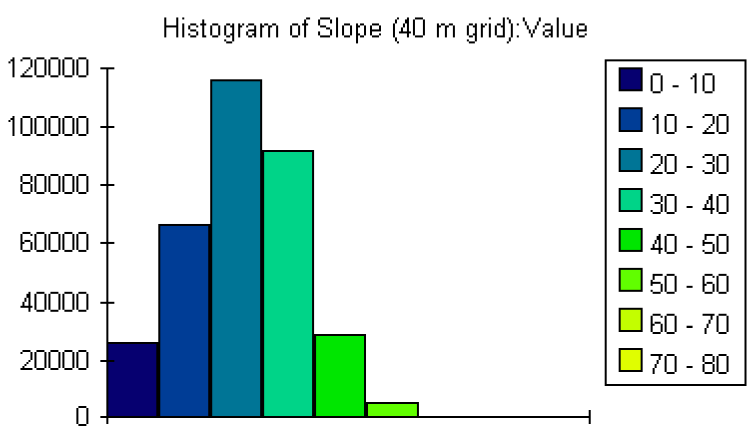

Fig. 5: Distribution of slope classes in Tseng-Wen watershed

2. Sampling of landscape units.

As originally planned we aimed at collecting a minimum 30 samples per watershed per year over a period of three year. This goal was reached and at this moment we have collected and analyzed 103 soil profile samples for Shih-Men and 104 for Tzeng-Wen respectively (see also Figure 2). In this paper however results of only 116 samples are presented as time constraints did not allow the analysis of recently sampled sites.

The sampling strategy followed methods as outlined by Zapata (2002). Samples were taken in different *a priori* defined landscape units as described in the above section. Hence, samples were taken in forests on low-medium, medium-high and high slopes, the same was done for farm land and grass land. In order to ensure samples represented a certain landscape unit, sites were chosen in the center of each land use type and complex - meter scale - topography was avoided. The reason being that ^{137}Cs inventories and associated erosion rates for each landscape unit need to be resolved in the GIS representation of the watershed, which has a resolution of 40 m. A handheld GPS with maximum positional error of about 10-15 m was used to record the location of each sample site.

Initial attempts to use a cylindrical corer failed since the soil appeared too hard or in other cases stones and tough bamboo roots prevented the core from reaching the minimum required sampling depth of 0.4 m. Therefore, all soil cores were collected using a more flexible configuration of three steel plates. Each plate has a length of 500 mm, width 150 mm, and thickness 2 mm with one end sharpened. They are hammered into the soil until a depth of 400 mm is reached. The three plates form a U shape that must prevent soil in higher layers from falling on to lower layers during sampling. Eight soil layers, of 0.05m each, are carefully removed from within the area bounded by the plates until the depth of 400mm is reached or earlier when soils are shallow. The surface area of each core is approximately 0.02 m^2 and each layer typically weighs around 1 kg (wet weight). Each sampled layer is dried and homogenized in the laboratory, and a sub-sample is analyzed for its ^{137}Cs activity concentration using four HPGe _-detectors simultaneosly. Counting times were typically 43200 seconds with analytical precision ±10%. .

Activity concentrations (unit: Bq/kg) for each layer are converted to activity per unit area (Bq/m^2) by multiplying with the specific soil density for the layer. Total inventories are than the sum of activity densities in all eight layers. The inventories for all sample sites are shown in Figure 6. Note, the yellow markers indicate locations of reference samples the meaning of which will be explained in more detail in the next section.

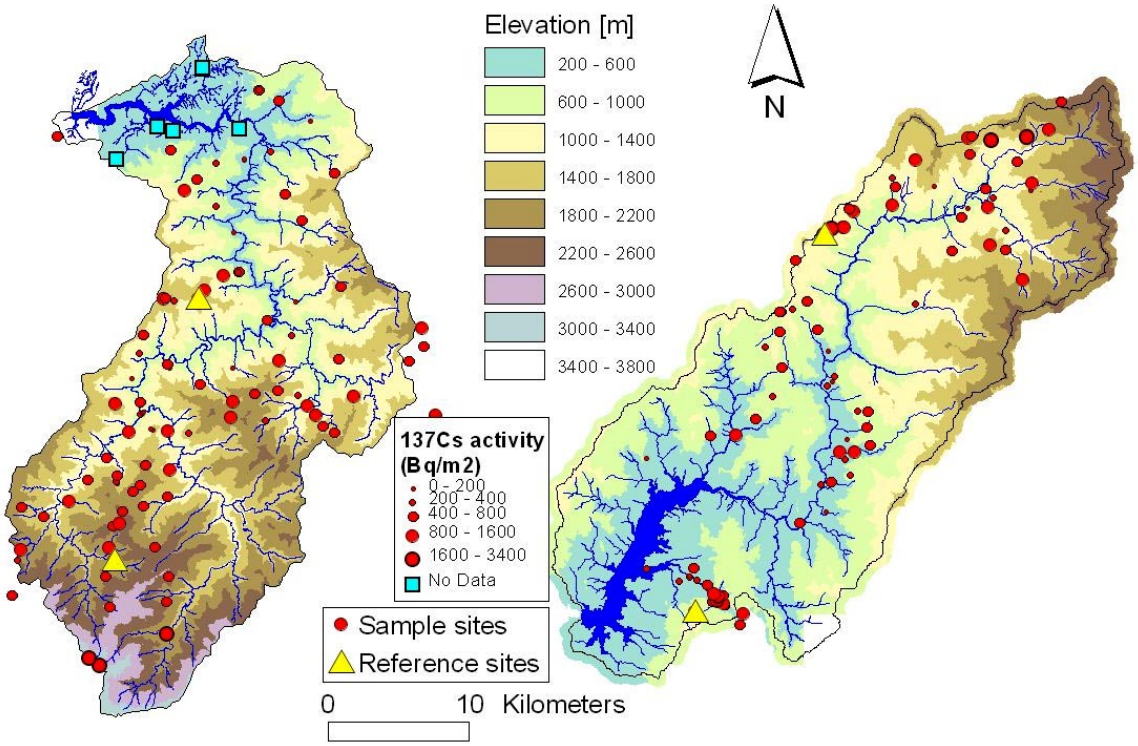

Fig. 6.: Sample activity densities and elevation of Shih-Men and Tseng-Wen reservoir watershed.

3. Identification of reference sites

The crux of the ^{137}Cs method is the identification of one or more reference sites within the watershed. These reference sites are assumed to be stable sites where no erosion or deposition has occurred in the past 40 years. As the term already indicates they are the reference to which the sample inventories are compared in order to know the loss (or gain) in ^{137}Cs and associated soil particles. At reference sites, the only change in ^{137}Cs activity levels is caused by natural decay (half-life is 30.2 year) which must be accounted for when samples are taken over a number of years. Criteria for the identification of reference sites are, prior to sampling: a position in flat undisturbed terrain with no upslope area, which may have acted as a source of ^{137}Cs.

After the radiological analysis further checks are necessary to determine if vertical distributions follow the expected exponential decrease with depth. Also the total activity values must be in accordance with known historical levels of ^{137}Cs deposition. From literature it is known that ^{137}Cs is mainly deposited in association with wet deposition (Davis, 1963; Rowan, 1995), so in Taiwan mainly with rainfall. In Figure 7 the annual average rainfall distributions for the two watersheds is shown. In both watersheds, rainfall amounts are strongly and positively correlated with elevation. Accordingly, the highest mountain areas in the south of Shih-Men and in the north of Tseng-Wen receive the most rainfall. However, the amount and also the variation of rainfall are highest in the Shih-Men watershed (left).

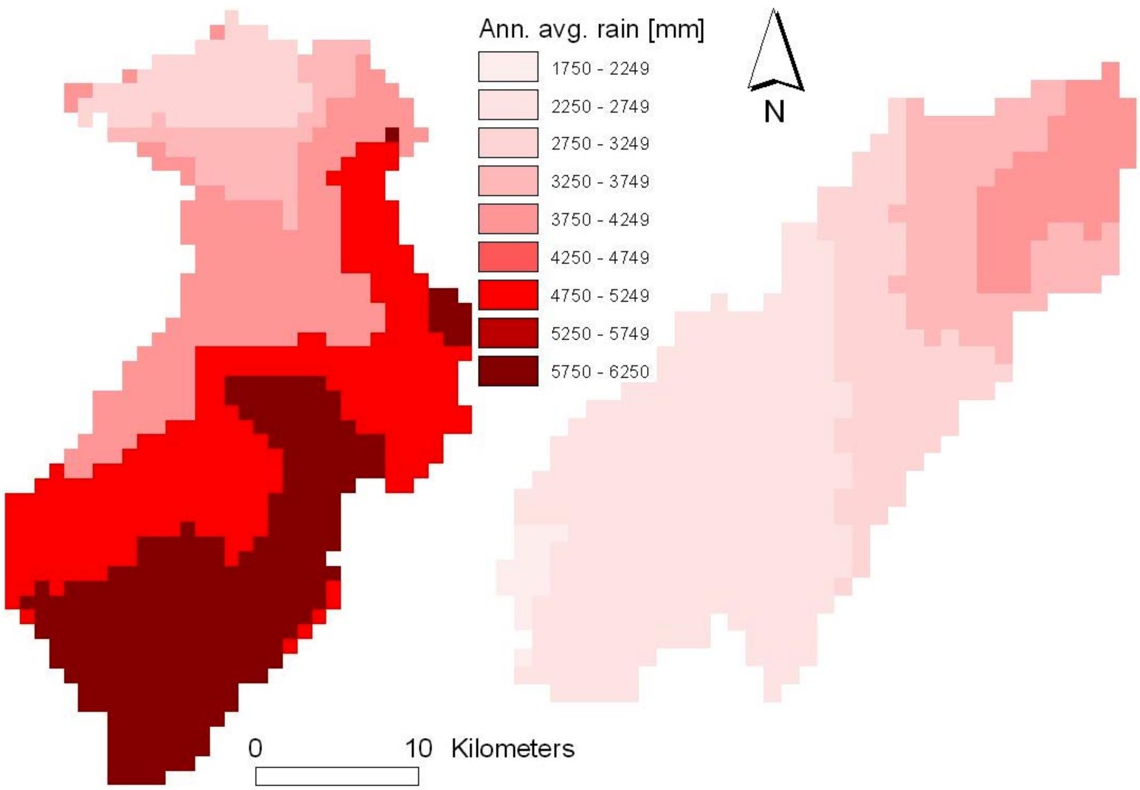

Fig. 7. Average annual rainfall (1961-1990) for the two reservoirs (CWB, 1960-1991).

In this paper we use four reference sites, (refer to Figure 6) two in each watershed, to account for the variation in rainfall. In the next section it is explained how erosion rates were calculated for each sample point.

4. Calculation of erosion rates

Once the vertical distributions of ^{137}Cs and the total inventories in the reference sites were known, mass-balance models proposed by Walling and He (1997), Zapata (2002) could be applied to convert ^{137}Cs activity densities for sample locations into soil erosion or deposition rates. Each watershed was divided in two parts and samples were assigned to the reference site in the corresponding part. We must stress again that the calculated rates represent the average net effect of erosion and/or deposition over the last 40 years.

Results

The results of calculations erosion rates for the Shih-Men watershed are given in Table 3 and for Tzeng-Wen in Table 4. The tables show the average erosion for each landscape unit (LSU). Meaning of LSU codes are as follows:

- L-MSl-for = forest on slopes less than 28°
- L-MSl-farm = farm land on slopes less than 28°
- M-HSl-For = forest on slopes between 28° and 56°
- M-HSl-farm = farm land on slopes between 28° and 56°
- HSl-for = forest on slopes more than 56°
- HSl-grass = grass on slopes more than 56°

The tables also show the total area that is covered by each LSU as well as the percentage of the watershed that is covered by all sampled LSU's, respectively 97% for Shih-Men and 89 % for Tzeng-Wen. Next to the area column the number of samples and standard deviation for average erosion rates in each LSU are given.

By multiplying the calculated average erosion rates by the area of the LSU and the number of years that the reservoir is operational we could calculate the total soil erosion amount for each LSU. This was done to show the relative importance of each LSU to the total soil erosion in the watershed over the past 40 years. Finally by summing the individual LSU erosion estimates we get the total erosion for the Shih-Men and Tzeng-Wen reservoir operations. Because we had records of the complete sedimentation history for Shih-Men reservoir (see Figure 8) we were able to compare what the contribution of

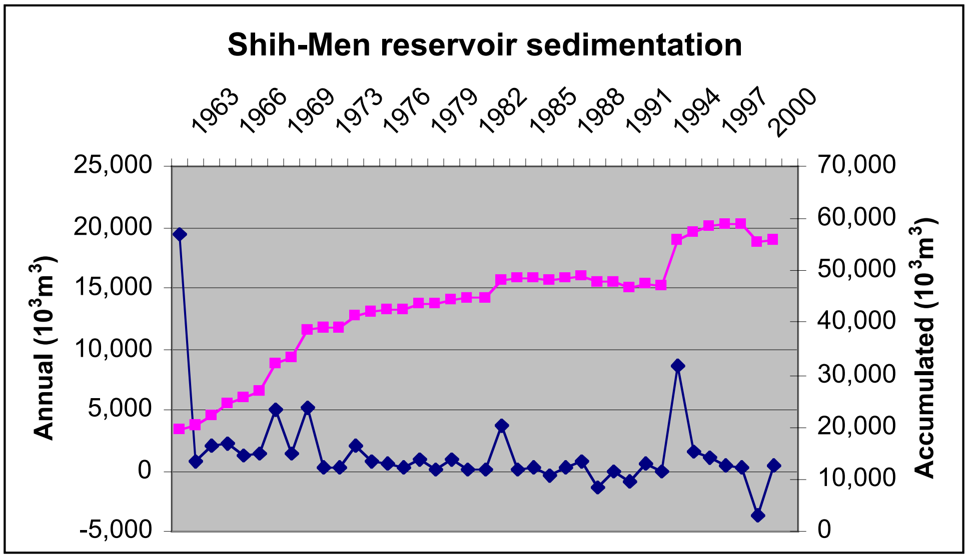

Fig. 8.: Sedimentation record of the Shih-Men reservoir (Water Resource Agency, 2004).

the calculated soil erosion to the total sedimentation was. It was found that more than 26% of total erosion is_due to soil erosion and so 73.8% caused by landslides or other sources. This agrees pretty well with an independent study that employed the so-called 'Power Law' method to calculate the total volume of sediment contributed by landslides into the Shih-Men reservoir for the same period. Regretfully, no sedimentation history for the Tzeng-Wen reservoir was available to verify our results. The forest area proves in both watersheds the largest contributor because it covers the largest area.

Table 3: Results for distributed erosion rates in Shih-Men watershed

Shih-Men	Area	N	Ave_Erosion	StdDev_Erosion	1964-2004	Total
LSU	Ha	-	10^3kg/ha·yr	10^3kg/ha·yr	No. of years	10^3 kg
L-MSI-for	5021	7	9.86	7.28	40	1980112
L-MSI-farm	439	1	35.78	0.00	40	628125
M-HSI-For	54323	43	10.31	9.21	40	22405864
M-HSI-farm	1584	5	18.94	10.19	40	1200656
HSI-for	11629	4	27.04	24.12	40	12578056
HSI-grass	59	1	11.18	0.00	40	26403
Total	**456599**	**61**				**38819215**
Total area	472438			Reservoir sedimentation '64-'04		148050200
Covered:	97	%		Contribution SE		26.2%
* Shih-Men reservoir office annual report				Contribution LS*		73.8%
**'Power Law' method				Contribution LS** SDR		119982120
				Contribution LS**		81.0%

Table 4: Results for distributed erosion rates in Tseng-Wen watershed

Tseng-Wen	Area	N	Ave_Erosion	StdDev_Erosion	1973-2004	Total erosion
LSU	Ha	-	10^3kg/ha·yr	10^3kg/ha·yr	No. of years	10^3 kg
L-MSl-for	19347	25	22.33	14.02	31	13394632
L-MSl-grass	649	1	34.02	0.00	31	685419
L-MSl-farm	4469	16	30.78	16.56	31	4264262
M-HSl-for	18408	11	19.42	14.14	31	11082498
Total	**281185**	**53**				29426810
Total area:	314681					
Covered:	89	%				

The erosion rates calculated for each LSU were distributed over the watershed using a GIS to combine the landscape units with the calculated erosion rates, the results are shown in Figure 9 below.

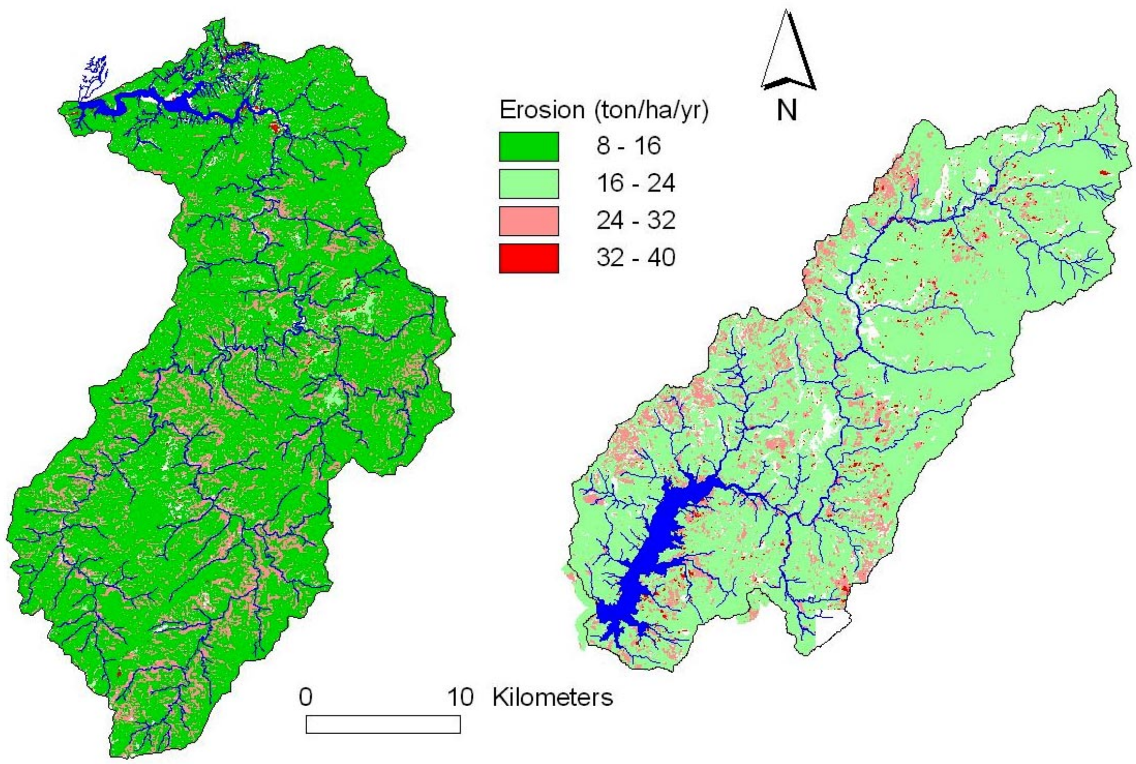

Fig. 9. Distribution of erosion rates across Shih-Men (left) and Tzeng-Wen (right).

Discussion

We applied the ^{137}Cs method to study erosion and sedimentation in two watersheds in Taiwan. Erosion rates presented in this paper were computed for 116 samples from a total number of 207 samples that were collected over a three year period. Erosion rates ranged from 1.15 to 71 ton per hectare per year. It was found that erosion of forested areas is higher in the Tzeng-Wen watershed, which can be attributed to the presence of easily erodible mudstone in large areas of the watershed as opposed to the harder rock types that are typically found in the Shih-Men watershed area. The erosion in Tzeng-Wen watershed is further limited to farm land – of which most are tea farms – mainly situated along the North West watershed boundary. Maximum erosion rates in Tzeng-Wen were calculated for grass slopes. Note however, that only one sample represented this LSU. On the other hand, grass areas occupy only a fraction of the total watershed, hence cannot be regarded as a significant source.

We found further that high erosion rates in Tzeng-Wen tend to be located further away from tributaries and streams. In the Shih-Men watershed relatively high erosion rates were found for forested areas in the highest slope classes (>56°), mainly close to tributaries and also along larger streams. If true, than this would implicate different lag times for eroded soil material in each watershed. The latter could be tested using gauging station monitoring data showing the time of peak sediment concentrations during storm events.

Figure 10 showed that standard deviation for each class are relatively high. This maybe in part caused by the limited number of samples that were available for study at the time of writing. But this may also be caused by the fact that reference inventories vary significantly across the watershed, a problem that was already addressed by VandenBygaart et al. (1999). The authors believe now that twelve or more reference sites evenly spread across the watersheds could eliminate this bias.

Another uncertainty is related to the land use map that shows the situation as it was in 1998. The authors realize that land use may well have changed during the last four decades. For example in an interview with a farmer in the Shih-Men watershed, we learned that his family started a tea plantation in the beginning of the last century, then changed to growing oranges some 70 years ago, and when oranges stopped being profitable longer, he switched to growing bamboo around 30 years ago. We heard a similar story in Tzeng-Wen, where tea farms were told to last for about 15 to 20 years, and after that only fruit trees or betel nut trees can grow in the degraded soil. This raises questions as to how representative erosion rates are for each combination of land use and slope, unless the land use history for each site is known.

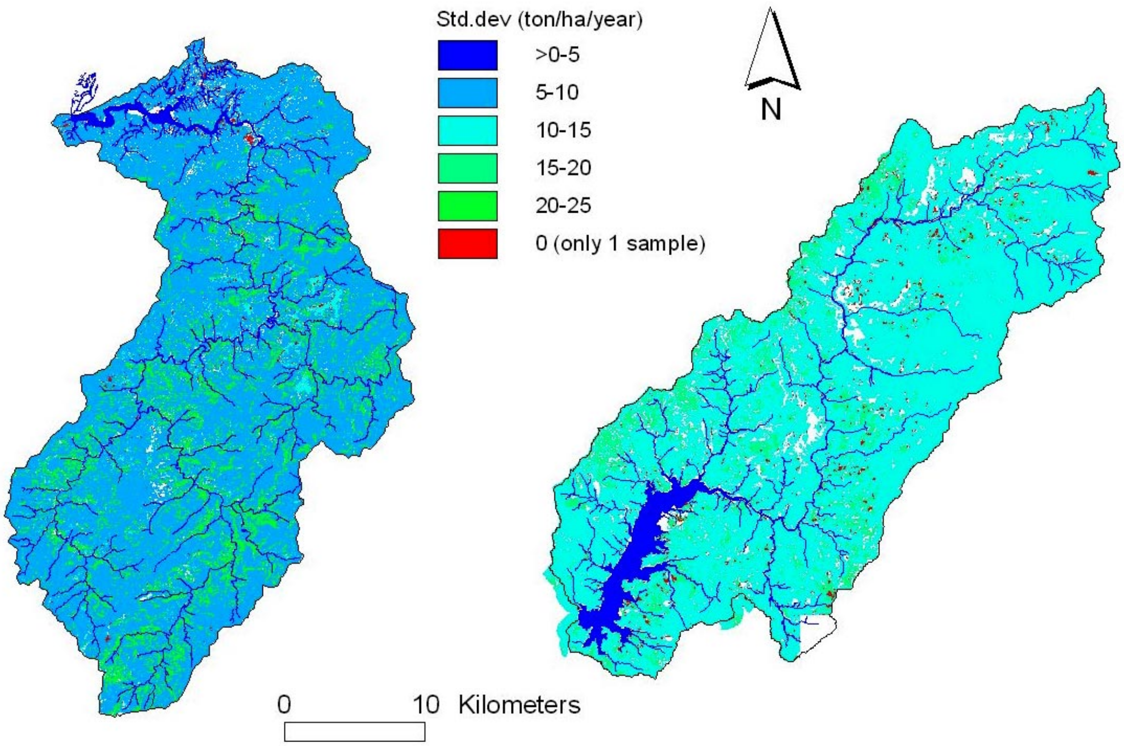

Fig. 10. Maps that show the standard deviation of erosion estimates for Shih-Men and Tzen-Wen..

Conclusion

The ^{137}Cs-method can in principle be applied to study the sources of reservoir sedimentation by estimating long-term soil erosion in the mountainous watersheds. Environmental ^{137}Cs activity levels are presently still high enough to be measured in the laboratory with good accuracy. The results of this study show that soil erosion in forested areas contribute the most sediment since they occupy the largest area. The highest average erosion rates however were calculated to farms and grass land on low to medium slopes 34.0 and 35.9 tons per hectare per year respectively. When comparing the total soil erosion for the Shih-Men watershed with the total sedimentation in the Shih-Men reservoir the authors found that soil erosion accounted for about 26% of the total sedimentation. This is in reasonable good agreement with another study that calculated the contribution from landslides as being around 80%. Uncertainties in erosion rates were reflected in the relatively large standard errors. One reason was the limited number in some landscape units. However, the erosion estimates were further complicated by the fact that an often made assumption about reference values was found to be invalid. The assumption that initial ^{137}Cs fallout was uniform cannot be true for (sub) tropical mountainous areas. Because rainfall amounts vary over the watershed, original deposition of ^{137}Cs will have varied accordingly. In a further study the effect of observed rainfall variations will be reduced by increasing the number of reference sites from only two now to twelve.

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