Sediment delivery and budgets in reservoir watersheds

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Abstract Serious siltation of Taiwan’s reservoirs has occurred from natural landslides and over-development. Although reservoirs can be dredged to prolong their utility and there are treatments to improve water quality, it is far better to achieve these goals via effective watershed sediment management. The sediment budget concept represents the most basic framework for addressing sediment issues in reservoir watersheds. The Soil Erosion Index Model (SEIM) has been integrated into a geographical information system (GIS) to provide a basis to evaluate sediment delivery and budgets in reservoir watersheds. Soil losses estimated using SEIM have also been compared with estimates of soil movement using $^{137}$Cs. The sediment delivery processes occurring in the Shih-Men, Teh-Chi and Cheng-Wen reservoirs have been modelled using SEIM and landslide volumes. Results indicate that the sediment delivery ratios are 29, 67 and 75% for the Shih-Men, Teh-Chi and Cheng-Wen watersheds, respectively, when fluvial transport is disregarded. Sediment budgets have been developed in the 18 sub-watersheds of the three reservoirs. The approach developed during the present study not only provides erosion and landslide information at the individual sub-watershed level, but also establishes overall watershed sediment budgets. Finally, sediment budgets for the Shih-Men, Teh-Chi and Cheng-Wen watersheds are discussed in terms of their implications for sediment/watershed management.

Key words caesium-137; sediment budget; sediment delivery ratio (SDR); sediment yield; soil erosion index model (SEIM); soil erosion potential

INTRODUCTION

Substantial siltation in Taiwanese reservoirs generally results from natural collapse (e.g. landslides) and anthropogenic activities (e.g. urbanization). In addition, with its steep terrain and torrential rains (typhoons, storms) leading to intense transient flows, Taiwan can experience severe sediment problems. Faced with both the increasing difficulty of developing new water resources, and the potential consequence of severe water shortages, it is essential for Taiwan to prolong the utility of existing reservoirs, and to protect the quality of the water supply. Although reservoirs may be dredged to prolong their life spans, and water may be treated to improve its quality, it is far better to achieve these ends through effective watershed sediment management. The sediment budget concept represents the most basic framework for assessing and understanding sediment mobilization and delivery within reservoir watersheds. Before designing a monitoring network to measure the requisite components for establishing a sediment budget, it can be instructive to develop an approximate budget from the data obtained by field investigations, laboratory experiments, and measurements in similar
watersheds. Although attractive as a concept, the development of sediment budgets is, however, hampered by the problems of documenting rates of sediment mobilization, transport, and storage, which are likely to be characterized by significant spatial and temporal variability (Walling, 1998). Historical watershed data covering erosion and sedimentation are required to establish a sediment budget to: (a) compare the relative contributions from various parts of a watershed; and (b) to determine the relative significance of various sections within the watershed that have different response times. This current study presents a technique which estimates detailed sediment budgets through the use of the Soil Erosion Index Model (SEIM), integrated into a geographical information system (GIS) framework, and reports the results for three reservoir watersheds as an example of its application.

APPLICATION OF THE SOIL EROSION INDEX MODEL

Introduction to the SEIM

Chen et al. (1998) developed the Soil Erosion Index Model (SEIM) to estimate rates of soil erosion in natural environments in Taiwan. This model includes five factors affecting soil erosion: (a) soil properties; (b) rainfall; (c) terrain conditions; (d) land use; and (e) vegetation. These factors were established on the basis of field data, collected on erosion in Taiwan (Fig. 1). The method for calculating each index value is:

**Soil property index (KI)** There are two ways to calculate the soil property index, KI. One is to substitute the local soil properties into the Universal Soil Loss Equation (USLE) to obtain the $K_m$ value, which is then substituted into equation (1) to yield the $KI$ value. The other method is to use the results of soil investigations, such as those conducted in Taiwan by Hsieh & Wang (1991).

$$KI = 200 \times K_m$$  \hspace{1cm} (1)

**Rainfall index (RI)** The rainfall index value can be derived from the monthly rainfall standard deviation value $S_p$ (mm) and the annual precipitation $R$ (m):

$$RI = S_p \times R / 50$$  \hspace{1cm} (2)

**Slope Index (TI)** The slope index value is calculated using the average slope and equation (3) for determining the slope steepness factor:

$$TI = 10 \times S$$  \hspace{1cm} (3)

![Fig. 1 Schematic diagram of the soil erosion index model (SEIM).](image-url)
Cover index \((CI)\) The initial value of the cover index uses the cover ratio \(C_m\) value as a reference factor. Given the surface cover ratio \(C_m\) and substituting it into equation (4) yields the cover index \(CI\):

\[
CI = 20 - (20 \times C_m)
\]

Land-use index \((UI)\) The \(UI\) index is calculated using the soil erosion quantity relationship for different landuses and the relationship between the percentage of development and soil erosion reported by Chen et al. (1998). The \(UI\) values of the land-use index can be derived from equation (5):

\[
UI = U_0 / 8.5
\]

Soil erosion index \((AI)\) The index values for each factor can be obtained by employing equations (1)–(5), whereas the soil erosion index can be obtained by combining all five factors as equation (6). The Soil Erosion Index Model (SEIM) was established by applying regression analysis to the observed soil erosion field data, and the total of the index values obtained from equation (6):

\[
AI = KI + RI + TI + CI + UI
\]

For better simulations, the regression model has been divided into two parts depending on whether or not \(AI\) is less than 50 (equation (7)), or greater than 50 (equation (8)). Equations (7) and (8) show the relationship between the soil erosion quantity and the total index values:

\[
SE = 6 \times 10^{-7} AI^{5.12} \quad \text{with } AI \leq 50
\]

\[
SE = 0.233AI^{1.83} \quad \text{with } AI > 50
\]

The \(SE\) in the foregoing equations is the soil erosion quantity \(\text{t ha}^{-1} \text{ year}^{-1}\) of the index model, and \(AI\) is the total index value. Creating two separate equations ((7) and (8)) not only enhances the utility of the regression analysis, but also avoids under–estimating medium values of soil erosion (Chen et al., 2001).

Analysis of the soil erosion potential

Based on the requirements for the SEIM, data were collected on rainfall, landforms, soil properties, land cover, and land use; estimated soil erosion potential was then plotted using Surfer 6.0 and ArcView software (Fig. 2). The combination of a Windows-based module and the SEIM can provide expanded ranges and rapid calculations, and may represent a trend in natural resource studies (Fig. 3).

Comparison with \(^{137}\text{Cs} \) research

The use of \(^{137}\text{Cs} \) measurements as a means of estimating rates of soil loss and patterns of soil redistribution in the landscape is now well established and documented (Lee et al., 2002). Estimates of soil erosion computed by the SEIM have been compared with estimated rates of soil loss based on measurements of \(^{137}\text{Cs} \) activity in the soil. The
applicability of the SEIM model was assessed by comparing measured and model-derived data for the Shih-Men reservoir. Soil samples from the Shih-Men watershed for establishing $^{137}$Cs depth profiles and areal activity densities had been collected previously (Lee et al., 2002). The soil losses computed from the depth distribution of $^{137}$Cs are presented in Fig. 4. The soil erosion rates for the individual sampling points were estimated from the depth distribution of $^{137}$Cs; the mean value is smaller than the result computed by USLE, but is close to the result computed by the SEIM.
Fig. 4 Plot of soil loss based on the depth distribution of $^{137}$Cs (Lee et al., 2002).

ANALYSIS OF SOIL EROSION POTENTIAL IN RESERVOIR WATERSHEDS

In this study, the SEIM results form the basis for assessing soil erosion potential in reservoir watersheds. The Shih-Men watershed was divided into seven sub-watersheds and subsequently, the erosion potential for each subunit was calculated (Fig. 5(a)). The foregoing results show that soil erosion indices ($AI$) range between 17.5 and 26.1; the mean soil erosion index value is 21.4 ($AI$). Accordingly, annual soil erosion for the watershed ranges between 1.9 and 10.8 t ha$^{-1}$ year$^{-1}$; the mean annual soil erosion was estimated at 3.9 t ha$^{-1}$ year$^{-1}$. Further, the mean annual depth of soil loss was estimated at 0.3 mm. Field data indicate that annual losses in the Shih-Men watershed range between 0.1 and 5.0 mm over the period 1976–1998 (Chen et al., 2002). In Taiwan, basin sediment, in the main, includes material from both soil erosion and landslides. Assuming that the ratio of soil erosion to basin sediment in the Shih-Men Reservoir watershed is 25%, and the sediment delivery ratio is 48% (Chen & Lai, 1999), then the estimated annual sediment yield is 400 000 m$^3$ and the annual depth of soil loss is 0.5 mm. Hence, the predicted results fall within measured field data.

Similarly, the Teh-Chi and Cheng-Wen reservoir watersheds were subdivided into 25 and 16 sub-basins, respectively; subsequently, as with the Shih-Men watershed, individual estimates of the soil erosion potential were calculated (Fig. 5(b),(c)). The mean index values of soil erosion potential ($AI$) and annual soil loss in the Teh-Chi and Cheng-Wen reservoir watersheds are 24.3 and 7.5 t ha$^{-1}$ year$^{-1}$, and 36.0 and 55.7 t ha$^{-1}$ year$^{-1}$, respectively. Additionally, the mean annual depths of soil loss for the Teh-Chi and Cheng-Wen reservoir watersheds are 0.5 and 4.0 mm, respectively. Field data
Fig. 5 Soil erosion potential plots: (a) Shih-Men, (b) Teh-Chi, and (c) Cheng-Wen reservoir watersheds, respectively.
indicate that soil losses between 1976 and 1998 in the Teh-Chi watershed range
between 0.1 and 4.0 mm, whereas those for the Cheng-Wen range between 0.1 and
9.0 mm (Chen et al., 2002). Assuming the ratio of soil erosion to basin sediment in the
Teh-Chi and Cheng-Wen reservoir watersheds are both 15%, and the sediment
delivery ratios are 23 and 30%, respectively (Chen & Lai, 1999), annual sediment
yield in the Teh-Chi watershed is equal to 490 000 m$^3$ and the annual depth of soil loss
is 0.8 mm, whereas annual sediment yield in the Cheng-Wen watershed is equal to
3 900 000 m$^3$ and the annual depth of soil loss is 8.0 mm. Consequently, the predicted
results again fall within measured field data.

SEDIMENT BUDGETS IN RESERVOIR WATERSHEDS

The sediment budget concept represents a basic framework for assessing erosion and
sediment delivery in reservoir watersheds. Sediment budgets provide a means for
quantifying sediment mobilization, transport, and deposition in a basin. This study
employed the SEIM, in conjunction with measurements of suspended sediment and
landslide volumes, to assess sediment delivery processes occurring in the Shih-Men,
Teh-Chi, and Cheng-Wen reservoir watersheds. Sediment budgets were constructed
for all three watersheds by dividing each into six sub-basins to facilitate determination
of their respective sediment delivery ratios (SDR, Table 1). For this purpose, fluvial
input was ignored (assuming that the SDR for rivers is 100%) to simplify the
calculations. The results can be used to establish annual sediment budgets for all three
reservoir watersheds (Fig. 6). The main sources of gross sediment are both sub-basins I
and II in the Shih-Men and Teh-Chi reservoir watersheds, and sub-basins I and V in
the Cheng-Wen reservoir watershed. The SDR values for the three watersheds are 29,
67 and 75% in the Shih-Men, Teh-Chi, and Cheng-Wen reservoir watersheds, respec-
tively, assuming that the associated river systems are at equilibrium relative to
sediment supply and demand. In other words, if the SDR is greater than the value
given above, the river system becomes the main sediment source for the watershed. On
the other hand, the river system would represent the main site for sediment storage in
the watershed if the SDR is lower than the value given above.

Overall, the estimated SDR for the three watersheds emphasizes that only a
relatively small proportion of eroded soil from the upland sections of each catchment
actually reach the watershed outlet. The sediment budgets for the Shih-Men and

<table>
<thead>
<tr>
<th>Shih-Men reservoir sub-watershed</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
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<tr>
<td>SDR</td>
<td>0.18</td>
<td>0.06</td>
<td>0.81</td>
<td>0.17</td>
<td>0.68</td>
<td>0.67</td>
</tr>
<tr>
<td>Teh-Chi reservoir sub-watershed</td>
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<td>II</td>
<td>III</td>
<td>IV</td>
<td>V</td>
<td>VI</td>
</tr>
<tr>
<td>SDR</td>
<td>0.91</td>
<td>0.95</td>
<td>0.68</td>
<td>0.53</td>
<td>0.42</td>
<td>0.69</td>
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<tr>
<td>Cheng-Wen reservoir sub-watershed</td>
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<td>II</td>
<td>III</td>
<td>IV</td>
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<td>VI</td>
</tr>
<tr>
<td>SDR</td>
<td>0.89</td>
<td>0.97</td>
<td>0.99</td>
<td>0.67</td>
<td>0.44</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Fig. 6 Mean annual sediment budgets: (a) Shih-Men, (b) Teh-Chi, and (c) Cheng-Wen reservoir watersheds, respectively.
Cheng-Wen watersheds indicate a decrease in SDR with increasing watershed size, due to greater soil conveyance losses between their respective upland sections and their rivers. However, this relationship is not absolute for the Teh-Chi watershed, where hydrology and topography appear to be more important than watershed size, and where landslides appear to yield the most sediment.

The sediment budgets presented in Fig. 6 also could afford a basis for designing sediment control and management strategies for reducing the efficiency of sediment delivery from the individual areas to the river systems, and increasing storage elsewhere in the watershed. Additional reductions also could be achieved by reducing sediment output through the construction of wetlands and the use of buffer strips. Placement of such structures could be facilitated by using the results from the estimated sediment budgets.

CONCLUSIONS

The SEIM requires data on rainfall, landforms, soil properties, land cover, and land use; it can then be used to estimate soil erosion potential for the subsequent development of sediment budgets. In this study, the results obtained using the SEIM appear to be better than those obtained using the USLE. The estimated sediment delivery ratios for the Shih-Men, Teh-Chi, and Cheng-Wen watersheds are 29%, 67%, and 75%, respectively, when fluvial inputs are disregarded. The approach used in this study not only provides erosion and landslide information on an individual sub-basin level, it also provides a method for estimating overall watershed sediment budgets. The river system is the main sediment source in reservoir watersheds if the actual SDR is greater than the estimated value. On the other hand, the river system is the main site of sediment storage in the watershed if the actual SDR is smaller than the estimated value. Sediment budgets can be constructed and modified based on an analysis of the SDR, and an evaluation of soil erosion, suspended sediment loads, and landslide volumes. The development of these budgets can be used to identify the most appropriate sites for instituting various remediation measures, designed to limit the impact of excess sediment in reservoir watersheds.

REFERENCES


