Using Multi-scale Sediment Monitoring Techniques to Evaluate Remediation Effectiveness of the Tsengwen Reservoir Watershed after Sediment Disasters Induced by Typhoon Morakot

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ABSTRACT: The 2009 typhoon Morakot dumped more than 3,005 mm of rain in mountain areas of the Tsengwen reservoir watershed and caused unprecedented landslide and sediment-related disasters. Subsequently, the storage capacity of the Tsengwen reservoir was drastically reduced. In order to increase the longevity of the reservoir and also protect ecosystems and the peoples living in the upper portions of the watershed, the Taiwan Executive Yuan implemented the "Tsengwen, Nanhua, Wushantou Reservoir Remediation and Water Resources Protection Act". This study aims to use multi-scale sediment monitoring techniques including field investigations and multi-stage remote sensing data to identify sediment migration patterns associated with remediated areas of the Tsengwen reservoir watershed after typhoon Morakot and to guarantee the effectiveness of remediation efforts. A case study of the Longjiao creek in Tsengwen Reservoir watershed shows that remediation works can not only reduced sediment production due to erosion and landslides, but future sediment production will also be suppressed. The reduction of sediments carried by the Tsengwen river will also lead to an increase in the service life of the Tsengwen reservoir.

RÉSUMÉ : En 2009, le typhon Morakot a déversé plus de 3 005 mm de pluie dans les régions montagneuses du bassin versant du réservoir et provoqué des glissements de terrain Tsengwen sans précédent et les catastrophes sédiments. Par la suite, la capacité de stockage du réservoir Tsengwen a été considérablement réduit. Afin d'augmenter la longévité du réservoir et aussi de protéger les écosystèmes et les populations vivant dans les parties supérieures du bassin versant, le Taiwan Yuan exécutif mis en place le "Tsengwen, Nanhua, Wushantou réservoir d'assainissement et de protection des eaux Loi sur les ressources". Cette étude vise à utiliser multi-échelle des techniques de surveillance des sédiments, y compris les enquêtes sur le terrain et sur plusieurs périodes données de télédétection pour identifier les schémas de migration des sédiments associés à des zones assainies du bassin versant du réservoir Tsengwen après le typhon Morokot et de garantir l'efficacité des efforts d'assainissement. Une étude de cas du flux Longjiao dans le bassin versant du réservoir Tsengwen montre que les travaux de réhabilitation peuvent non seulement réduit la production de sédiments à cause de l'érosion et des glissements de terrain, mais la production de sédiments avenir seront également supprimés. La réduction des sédiments charriés par le fleuve Tsengwen conduira également à une augmentation de la durée de vie du réservoir Tsengwen.

KEYWORDS: Tsengwen reservoir watershed, typhoon Morakot, sediment disasters, remediation effectiveness.

1 INTRODUCTION

In 2009, typhoon Morakot brought heavy rainfall up to 3,005 mm, which was recorded at Alishan rainfall guage station of the Tsengwen reservoir watershed over a five day period. Also, the consecutive 72 hour accumulated rainfall exceeded historical records in Taiwan (SWCB, 2011). This typhoon event induced massive sediment-related disasters within the watershed, which caused about 91,080,000 m^3 of sediment in the reservoir and exceeded the original design level (5,610,000 m^3/yr). Afterward, Taiwan government passed “Tsengwen, Nanhua, Wushantou Reservoir Remediation and Water Resources Protection Act” and planned a project for managing and remediating sediment problems. The primary goals of the proposed project are to reduce reservoir turbidity levels, extend the service life of the dam and protect security of the upstream residents.

Sediment transport and deposit within the watershed is an unavoidable natural process. It is very important to do field survey and monitor periodically especially in major sediment source areas including old debris flow, large-scale landslide and massive alluvial soil or river terrace deposits. Many researches has pointed out that the sedimentation of Tsengwen Reservoir has been serious in flood season due to intense geological activity. Recently, under the effect of global climate change, the probability of extreme weather occurrence has increased. In the mountain area, it can be observed that the magnitude of disasters caused by water-sediment flows, induced by high intensity and long duration rainfall events, has increased (Lo *et al*., 2012; Lin *et al*., 2012). The mode of sediment transport can be classified in different ways, according to the mechanics of sediment transport process, from suspended load to debris flow. Therefore, the sediment deposited in the Tsengwen reservoir watershed comes from long-term deposits of the trunk river and soil erosion as well as slope landslides due to 2009 typhoon Morakot. It significantly affects water supply to residents and rapidly reduced storage capacity of reservoir. For validating and proving the effectiveness of remediation efforts after typhoon Morakot event, the study integrates multi-scale sediment monitoring techniques to collect time-dependent monitoring data and spatiotemporal remote sensing information including watershed scale, high-resolution airborne LiDAR DTMs. Then, using the data obtained from the remediated environmental area, remediation effectiveness of the Tsengwen reservoir watershed with regard to suppression of soil erosion, vegetative recovery rate, variation in amount of landslide and sediment trapping efficiency are quantified. Finally, the proposed procedure of this study will assist us to track remediation effectiveness, and reduce sediment yield entering a reservoir or trap eroded sediment for effective watershed management.

2 OVERVIEW OF ENVIRONMENT

2.1 *Study area*

As illustrated in Figure 1, the Tsengwen reservoir is located in the southwestern portion of Taiwan. It is the most important water resource conservation hydraulic structure and the largest dam in Taiwan. The dam is 400 m in width and 133 m in height, and mainly serves irrigation, municipal water and power supply functions for the southern plains and downstream area of Chiayi county, Tainan and Kaohsiung city shown in Figure 2. The watershed area of Tsengwen Reservoir is approximately 481 km^2, where Tsengwen river is the trunk river originating from Alishan mountain at elevation of 2,609 m a.s.l. The watershed shape is similar to a quadrilateral with elevations gradually increasing from southwest to northeast, and ranging from 100 m a.s.l and 2,700 m a.s.l. In general, most hill slopes are steeper than 28.8° and approximately represents over 60% of the study area. As for the aspect, slopes are mostly west-facing and southwest-facing in the watershed. There are many fault line and geologic structures and the geological condition of the watershed consists mostly of sandy shale, siltstone, and isolated areas of muddy sandstone, which are prone to more severe weathering and become weak layers in the rock strata. These conditions make the slope unstable during heavy rainfall or strong earthquake shaking. Hence, during the typhoon and flood season, the combination of huge rainfalls and local weak geological conditions easily permit the occurrence of sediment landslides (Lo *et al*., 2012).

Due to high topographic relief, annual average temperature ranges from 24℃ in the plains and 11℃ in the mountainous parts of the watershed. According to Alishan rainfall gauge station, average annual accumulated ranges from 1,950 to 4,980 ㎜. Recent extreme rainfalls have caused annual accumulated rainfall of Taiwan to increase, especially for Alishan, where, since 2005, annual rainfalls have exceeded 5,000 ㎜ (see Figure 3). This rate is double the annual average precipitation (2,500 ㎜) for Taiwan and over four times of world annual average precipitation. Rainfall distribution increases from the plains to the mountains and is mostly concentrated between May and September when the watershed receives approximately 80% of the overall annual rainfall.

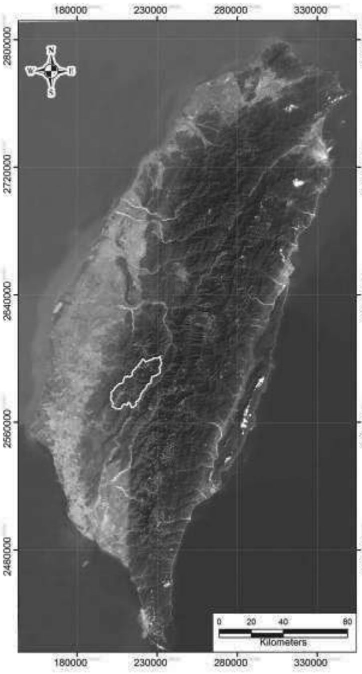

Figure 1. Graphical location of Tsengwen reservoir watershed i Taiwan (local coordinate system: TWD97).

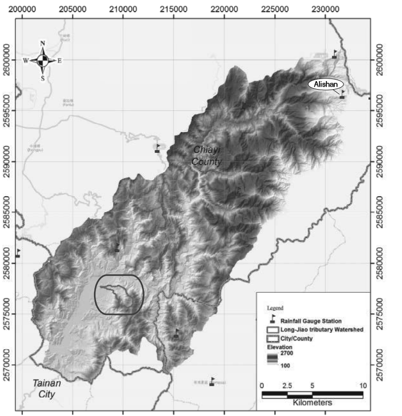

Figure 2. Topographic map of Tsengwen reservoir watershed (local coordinate system: TWD97).

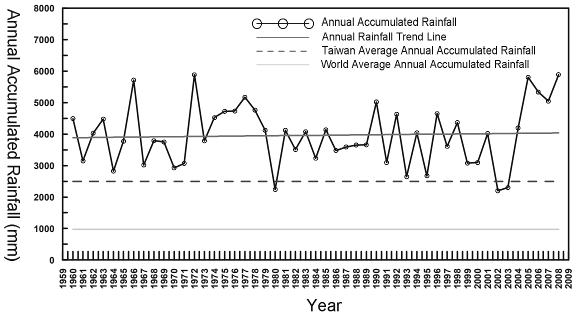

Figure 3. Time series of annual rainfalls at Alishan gauge station.

2.2 *Relation between reservoir sedimentation and major typhoon events*

Presently, the greatest challenge of Tsengwen reservoir is sedimentation. Whether caused by anthropogenic or natural factors, both of them directly triggers problems such as increased turbidity and reduced reservoir storage volume. Figure 4 illustrates the historical trends of sedimentation in Tsengwen reservoir concerning major typhoon events. According to the figure, since completion of reservoir construction, typhoons repeatedly hit the Tsengwen reservoir. It can be found that the peaks in the historical sedimentation curve of Tsengwen reservoir correspond to major typhoon events. Before 2008, the annual average sedimentation volume is 4,760,000 m^3 and still lower than the yearly designed value of 5610,000 m^3. However, 2009 typhoon Morakot brought around 91,080,000 m^3 of sediment into Tsengwen Reservoir, which occupies about 12% of the reservoir capacity. After the 2009 typhoon Morakot, the annual average sedimentation rapidly increases to 7,060,000 m^3, exceeding the yearly designed value by 12.6 times. It is truly believed that massive amounts of sediment washed downstream. Also, this event seriously resulted in debris flows and large large-scale landsides along river flanks and close to human inhabitation in upstream areas, and threatens longevity of reservoir and significantly affects water supply to the south area in Taiwan.

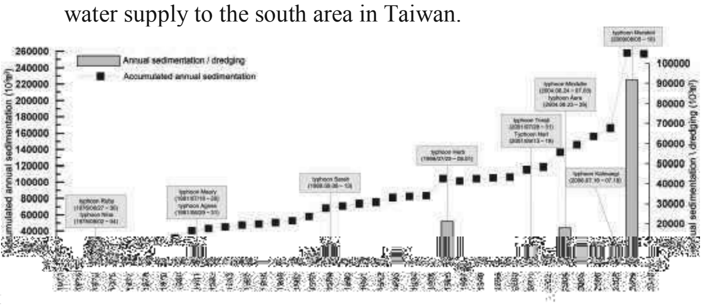

Figure 4. Historical sedimentation curve of Tsengwen reservoir with the major typhoon events

3 MULTI-SCALE SEDIMENT MONITORING AND EVALUTION METHOD TO REMEDIATION EFFECTIVENESS

Multi-scale sediment monitoring techniques is used in Tsengwen reservoir watershed to study remediation effectiveness and topographical changes. This section describes the method about how to systematically study and analyze soil erosion, landslide areas, and sediment trapping in the check dams from easily measured physical quantities such as depth, area, and volume by collecting time-dependent monitoring data and multi-stage remote sensing information in a watershed scale. A case study of the Longjiao subwatershed was chosen to be validated with remediation effort. The above proposed methods are detailed separately below.

3.1 Depth-based evaluation method

Soil erosion estimates were often based on empirical equations, such as USLE, MUSLE, and RUSLE, etc. These empirical equations are limited regionally and by spatial distribution of rainfalls. Therefore, this study focused on the different vegetated slopes to design erosion pins by some research reports (Schumn, 1956). Site surveys were conducted to measure surface erosion depth to investigate the state of slope soil after erosion from rainfalls. The result was used to assess the inhibition rate of soil erosion from both remediated and non-remediated hillslopes in order to understand the efficiency of remediation. To quantify the soil erosion suppression ratio (*SSR*) from the measured soil erosion depth of several erosion pins (see Figure 5) embedded in remediated and non-remediated hillslopes, we used an index value to depict efficiency of soil erosion retention after completing remediation. Higher index values indicate higher soil erosion suppression. Therefore, this study uses this index (*SSR*) to understand the remediation effectiveness of the hillslopes. *SSR* is defined as follows

$$SSR(\%) = \frac{E_{DR} - E_{DN}}{E_{DR}} \times 100\% \qquad (1)$$

Where *SSR* is soil erosion suppression ratio (%) ; E_{DR} is surface eroded soil depth of remediated hillslope (mm) ; E_{DN} is surface eroded soil depth of non-remediated hillslope (mm).

Figure 5. Schematic layout and photos of erosion pins embedded in remediated/non-remediated hillslope.

3.2 Area-based evaluation method

To understand the evolution of vegetation coverage of the Tsengwen reservoir watershed resulting from remediation efforts, multi-spectral high-resolution satellite images from different periods are adopted to analyze the ratio of green cover to assess the vegetation restoration after remediation. Normalized Difference Vegetation Index (NDVI) is currently a popular method to assess vegetation coverage (Kriegler *et al.*, 1969). The *NDVI* is calculated from these individual measurements as follows:

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \qquad (2)$$

where *VIS* and *NIR* stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively. The *NDVI* value is normalized between -1.0 to 1.0. Values of NDVI above a certain threshold correspond to vegetation coverage area and values below the threshold correspond to non-vegetation coverage areas, as shown in Figure 6.

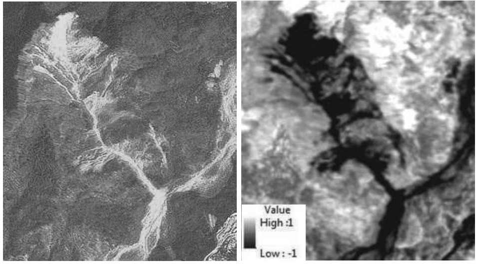

Figure 6. Orginal satellite image and the classified image from results of *NDVI*.

Once the NDVI has been used to classify the images into vegetated and non-vegetated zones, the ratio of vegetation coverage (*VR)* involved with the total area is estimated, as shown in Eq. (3).

$$VR(\%) = \frac{A_V}{A_C} \times 100\% \qquad (3)$$

Where A_c is a given watershed area, and A_v is vegetated area within a given watershed.

3.3 Volume-based evaluation method

This study compiled satellite images to identify the landslide distribution. Number of landslides, existing landslide area, incremental landslide area, and spatial distribution in key regions were obtained through digital interpretation to understand its evolution. Further, this was complemented with multi-period terrain data, established by airborne LiDAR, to quickly obtain information on terrain changes in each sub-catchment area and assess the effectiveness of the remediation projects. To evaluate the effectiveness of check dams, this study utilized airborne LiDAR (Light Detection And Ranging) technology to survey and produce high resolution DEMs of the Tsengwen reservoir watershed. The pre-event DTM is subtracted from the post-event DTM. A negative value in the grid represents failure or erosion, and positive value indicates deposits. Variation in volume of a grid can be obtained by multiplying this value by the area of the unit grid (see Figure. 7). The total volume of landside material and sediment trapped by the check dam can also be obtained from multiple LiDAR generated DTMs. Then, sediment discharge and trapping efficiency of dams can be precisely calculated. It can also be applied to monitor the accumulated volume of sediment on the confluence between tributaries and river, growth of alluvial fan, and large scale wedge like slope failures. Comparison of LiDAR DEMs from different periods can also indicate terrain migration and be used to trace sediment transport from tributaries, especially in extreme typhoon disasters. Sediment trapping ratio (STR) can be assessed by measuring the volume of deposited sediment in front of the check dams (Sophie *et al.*, 2008). If *STR* after remediation is higher than before remediation, it means that check dams are effectively controlling sediment transport and have adequate remediation efficiency levels. The sediment trapping ratio can be expressed as：

$$STR(\%) = \frac{V_d}{V_y} \times 100\% \qquad (4)$$

Where V_d is the trapped volume in the check dam(m^3) ; V_y is the sediment yield from upstream (m^3).

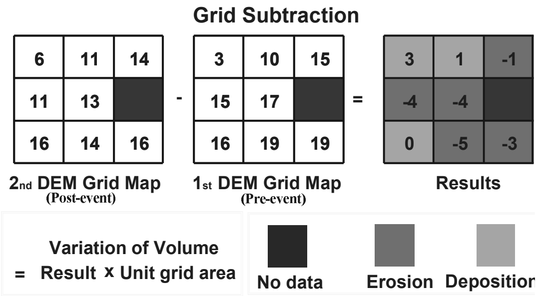

Figure 7. Grid subtraction in post-event and pre-event digital terrain elevations

4 CASE STUDY

In this paper, case study chooses Longjiao creek located at downstream area of Tsengwen Reservoir (see Figure 2) for proving the effectiveness of remediation efforts after typhoon Morakot, based on real data from multi-scale sediment monitoring techniques. Then, the proposed depth-area-volume based methods are all applied to evaluate the ratios of soil erosion suppression, vegetation coverage and sediment trapping in the following sections.

4.1 Soil erosion suppression

To effectively measure surface soil loss on remediated and non-remediated hillslopes, ten erosion pins were installed on each of the hillslopes types to monitor eroded soil depth for each rainfall events. The monitoring period is from May 14., 2011 to Oct. 04, 2011. Figure 8 is the diagram of the average accumulated eroded soil depth on remediated and non-remediated hillslopes. According to the figure, soil erosion of remediated hillslopes is obviously lower than the remediated. Compared with others, remediated hillslopes can reduce soil erosion by about 1.6 mm. This data is input into Eq. (1) and then the *SSR* of Longjiao subwatersehd is obtained as below :

$$SSR(\%) = \frac{18.7 - 7.25}{18.7} \times 100\% = 61.23\% \qquad (5)$$

The calculated result shows that remediation of hillslops could reduce erosion amounts by 61.23% of soil loss per unit area and time. It is evident that remediation can accelerate environmental vegetation recovery and under good practical sediment control.

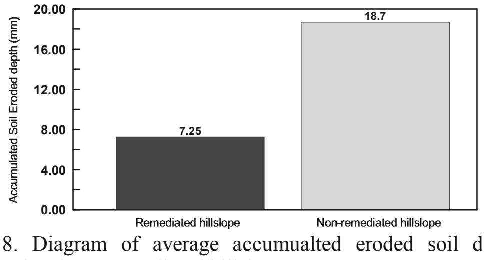

Figure 8. Diagram of average accumualted eroded soil depth on remediated and non-remediated hillslopes.

4.2 Vegetation coverage

Utilizing NDVI, multi-stage vegetation recovery of the overall Longjiao subwatershed after remediation was assessed for the five events. According to Eq. (2) and (3), the ratios of vegetation coverage were calculated. Figure 9 shows that after remediation, typhoon Fanapi and typhoon Namodol repeatedly affected Longjiao subwatershed but the vegetation coverage ratio (*VR*) still remained over 80%. This value was estimated by satellite images and is better than the ratio after typhoon Morakot. Again, these results show that remediation including check dams, river bed foundation, and revetment as well as excavation of deposited sediments, can effectively reduce sediment yield.

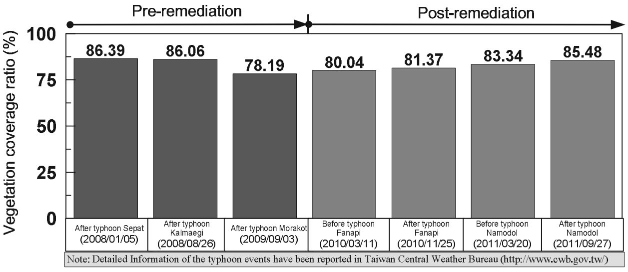

Figure 9. Evolution of vegetation coverage in pre-remediation and post-remediation for Longjiao subwatshed.

4.3 Sediment trapping

Soil and Water Conservation Bureau (2011) has collected three high-precision digital elevation models from aerial orthoimages and airborne LiDAR. These measurements can be divided into pre-remediation and post-remediation. Further, sediment yield is the total volume of terrain changes such as slope failures and river erosions by grid subtraction of DTMS. Sediment trapping ratio (STR) can be assessed by measuring the amount of sediment trapped in front of the check dams, which has been listed in Table 1. Compared with the results listed in table 1, post-remediation STR of Longjiao subwatershed is significantly higher than pre-remediation by 17.18 times. In the meantime, the sediment yield after remediation is lower than before remediation. Through the above results, it was found that sediment yields were effectively controlled.

Table1 List of Sediment trapping ratio of Longjiao subwatershed

Stages	Duration	Sediment yield (m^3)	Sediment trapping (m^3)	STR (%)
pre-remediation	2008~2010	1,548,300	34,540	2.2
post-remediation	2010~2011	149,143	56,373	37.8

5 CONCLUSIONS

This study systematically integrates multi-scale sediment monitoring techniques to analyze soil erosion, vegetation coverage, and sediment trapping from easily measured physical quantities such as depth, area, and volume in a watershed scale. Thorough the case study, it suggests that remediation in Tsengwen Reservoir Watershed are certainly effective and are able to reduce sediment production and soil loss entering a reservoir.

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