ON THE CORRELATION OF SEDIMENTATION AND LANDSLIDES IN WU RIVER CATCHMENT INFLUENCED BY THE 1999 CHI-CHI EARTHQUAKE

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ABSTRACT

This study investigated the correlation of catchment sedimentation and landslides in Wu River catchment before and after the 1999 Chi-Chi earthquake. In order to consider the flow discharge and sediment discharge in different sub-watersheds, analyses were performed for each sub-catchment with discussions. The results show strong correlation between the catch sedimentation and landslides. However, the impacts of Chi-Chi earthquake on different sub-catchments are different. A conceptual model is also developed to investigate the control factors on the correlation of sedimentation and landslides. This case study could provide experiences of the sustained landslide investigation and sediment estimation to regard as the reference of catchment management.

Key Words: Landslides, Catchment sedimentation, Dynamic environments, Chi-Chi Earthquake, Time effect, Wu River catchment

INTRODUCTION

The hilly Western Foothill of Taiwan Island is highly prone to landslides, especially during typhoon season in the summer. The 1999 Chi-Chi earthquake (MW=7.6) resulted in tremendous amount of landslides along the Wu River catchment of central Taiwan. The impact of this earthquake not only makes the geomaterial more fractured but also changes the river morphology in the Western Foothill area. This study investigated the correlation of catchment sedimentation and landslides before and after the 1999 Chi-Chi earthquake. The Wu River is a major river in central Taiwan, with 119km in length, 2025km^2 in drainage area. In order to consider the flow discharge and sediment discharge in different sub-watersheds, especially in the upstream, this study divides the Wu River catchment to three sub-catchments, the Peikang sub-catchment (I), Nankang sub-catchment (II), and mid to lower stream of Wu River (III). Analyses were performed for each sub-catchment with discussions. The study comprises two major parts, i.e., catchment sedimentation and correlation with landslides. The former part includes field, satellite image and DTM calculation results, and the later part includes analysis on the correlation between the landslides and catchment sedimentation. Following the 1999 Chi-Chi earthquake, two typhoon events, i.e., Toraji (2001) and Mindulle(2004), were adopted for this study.

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GEOLOGIC SETTING

The Wu River is sourced from Central Mountain Range, flows to the west through the Puli, Guoshing, paralleled with the Highway 14 until Tsaotun, from mountainous to the plains. It is a major river in central Taiwan, with 119km in length, 2025km^2 in drainage area, elevation from 3144m to 20m. For detailed analysis and discussion, this study divides the Wu River catchment to three sub-catchments, the Peikang sub-catchment (I), Nankang sub-catchment (II), and mid to lower stream of Wu River (III). (as shown in Fig. 1)

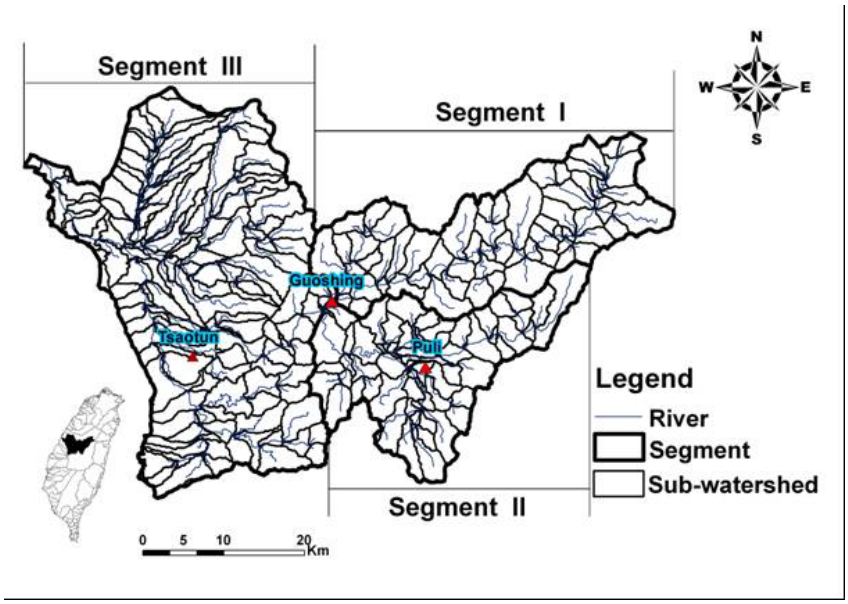

Fig. 1 Location, segments, and sub-watersheds of the Wu River in Taiwan

The Wu River catchment traverses three geological regions, including the Western Foothills, the Hsuehshan Range and the Central Range of Taiwan Island (Ho, 1994). Since the Wu River flows from the east to the west and the linear structures mainly trend in north-south direction, Wu River crosses several geologic formations with different geologic ages. Due to the vibrant tectonic activities, series of imbricated structures (including folds and faults) were formed in the north-south direction, as shown in Fig. 2.

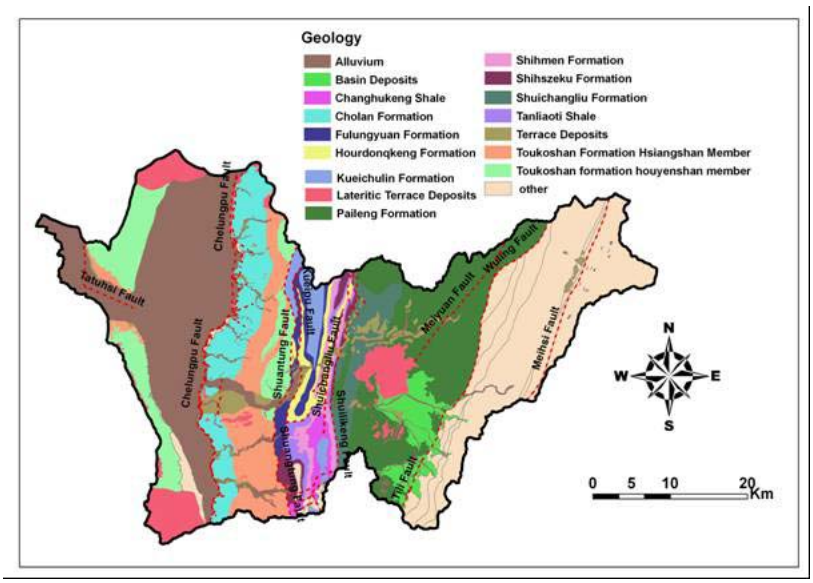

Fig. 2 Geologic map of the Ta-Chia River catchement

METHODOLOGY

Event-based landslide inventory

The databases of event-induced landslide inventory were originally established by the team of Sinotech and Moh (2008). In this study, both multi-spectral and panchromatic SPOT images were used. A fusing technique was utilized to produce a higher resolution false-color composite image to facilitate landslide recognition (Pan *et al.*, 2004; Nichol and Wong, 2005). Fused false-color SPOT images taken before and just after the Chi-Chi Earthquake were used for landslide recognition. Image interpretation was based on image tone, shape, association, and also personal experience. The landslides were digitized by ERDAS Imagine, and their attributes were also assigned and recorded. Each landslide was then checked against recent rectified aerial photographs. The landslides and their attributes were further calibrated and modified by ground truth obtained by field investigations. Complete pre-event and post-event inventories for the adopted typhoon events were obtained.

Catchment sedimentation analysis

The study applied the catchment sedimentation databases originally established by the Disaster Prevention Research Center of National Cheng Kung University (DPRC, NCKU, 2008). Topographic surveying of the chosen landslides, alluvial fans and cross sections of flow channels was performed to generate digital elevation models (DEMs). The temporal and spatial variations of the sediment yield and transport could be estimated by comparing the DEMs generated in different time periods. Samples of bed materials were taken for particle size analysis, and the coefficient of roughness was obtained for model calibration. The results of field survey and field instrumentations were used to calibrate the sedimentation analysis model and obtain the coefficients for the sedimentation analysis. After calibration and verification, the adopted typhoon events were simulated to evaluate the variation of sediment budget.

Conceptual model for the analysis of the correlation

In order to analyze the control factors and correlation of catchment sedimentation and landslide, an equilibrium equation was derived for the transportation of sediment. Then the major terms in the equilibrium equation were analyzed with consideration of their control factors.

Considering the sedimentation of a sub-watershed unit, we introduce a Sediment Deposition Index (Is), defined as

$$Is = \frac{Vs}{As} \tag{1}$$

where Vs is the sediment deposited in the catchment unit, As is the area of the sub-watershed unit.

For a five unit (sub-watershed) system, the sediment in sub-watershed unit i is determined by upstream unit i+1, j, k, and the downstream unit i-1 (see figure 6). The equilibrium equation can be rearranged as:

$$\frac{\Delta Vs,i}{As,i} = \frac{\Delta Vp,i + [(\Delta Vb,i+1) + (\Delta Vb,j) + (\Delta Vb,k) - (\Delta Vb,i)]}{As,i} \tag{2}$$

$$= \frac{\Delta Vp,i}{As,i} + \frac{\Delta Vr,i}{As,i}$$

The first term ΔVp,i/As,i represents the contribution of the sediment production in the unit and the second term ΔVr,i/As,i represents the contribution of the net sediments transported into the unit. Therefore, this study introduces two indexes, i.e., sediment generation index I_P and sediment transportation index I_R, to evaluate their contributions to the sediment deposition in a sub-watershed unit. Both of the indexes are strongly related to landslides, but their correlations are different.

1. Sediment generation index (I_P)

The I_P is closely related to landslide in the sub-watershed. Therefore, the landslide-related control factors were considered. Based on the importance and accessibility, we selected six major control factors, i.e., slope angle (Sa), dip slope index (Id), maximum rainfall intensity (Rm), cumulative rainfall (Rt), frictional angle (φ) and the landslide area ratio (RL) for the multi-variable analysis of the contribution of sediment generation. The Ip can be considered as a function of control factor scores and their weighting factors.

$$I_P = D_1^{w1} \times D_2^{w2} \times ... \times D_6^{w6} \tag{3}$$

where D1~D6 are the evaluation scores of the six control factors, and w1~w6 are the corresponding weighting factors.

The scores of control factors are normalized to 1~10 and determined by their classification, which is based on the distribution of average sediment generation associated with the specific control factor. A classification can have 5 to 10 ranges, according to the most common applications and the property of the factor.

For the analysis of I_P, 20 m× 20 m resolution databases of those control factors were created. The dip slope index is defined as the dip direction difference of the slope and the formation; the map of dip slope index was obtained by subtraction the dip direction of slope by the dip direction of formation, which are created by kriging the topography and geology data. The maps of maximum rainfall intensity and cumulative rainfall are obtained by kriging the records from the rainfall stations. The map of frictional angle φ is also obtained by kringing the geologic data, i.e., the average internal friction angle of formations. The landslide area ratio is obtained by the landslide inventory data.

2. Sediment transportation index (I_R)

For I_R, the characteristics of the river are crucial play major roles. Therefore, the multi-variable analysis of IR adopts six channel related control factors, including landslide

area ratio RL and river morphology parameters channel width Wd, channel length Le, gradient of channel Rs, gradient of river bank Bs, and sinuosity of the channel segment Si.

$$I_R \propto Wd, Le, \frac{1}{Rs}, \frac{1}{Bs}, Si, \frac{1}{R_L} \tag{4}$$

The I_R can also be expressed as a function of control factor scores and their weighting factors, similar to Eq. (3). In a similar way, the normalized scores are determined by classifications, and the weighting factors are determined by the coefficients of variance. However, considering the inherent meaning of sediment transportation, we replace the average sediment generation by a sediment transportation ratio. Sediment transportation ratio is defined as

$$R = \frac{\Delta Vs,i}{\Delta Vb,i} \tag{5}$$

where ΔVs,i is the net increase of deposited sediment and ΔVb,i is the sediment outflow. Since the sediment transportation ratio R is not symmetric, normalization is implemented in the normalized transportation ratio R'

For the analysis of I_R, the databases of river morphology parameters, including channel width, channel length, gradient of channel, gradient of river bank, and sinuosity of channel segment were created from the 5 m× 5 m DTM. However, a formula was implemented in ArcGIS (Version 9.0) to obtain the map of sinuosity. In addition, a Fortran program was established to obtain the normalized sediment transportation ratio R' of the sub-watershed in the catchement. The Ta-Chia River catchment is divided to 263 sub-watersheds for analyses (see figure 1). In order to investigate the correlation of catchment sedimentation and landslides, multi-variable analysis method was applied to study the influence of landslide on these two contributions, i.e., sediment generation and sediment transportation.

RESULTS AND DISCUSSION

Analysis of landslide and sedimentation

As described previously, SPOT images, aerial photos, DTMs, and field investigations were used for landslide mapping. These images were interpreted to produce landslide inventories of the typhoons Toraji and Mindulle. Comparing with typhoon Mindulle, about 5.25, 8.94, and 5.47 times more sediments were generated by typhoon Toraji in sub-catchment I, II, and III.

Considering the transportation of sediment, sediments accumulated in sub-catchment I is about 2.78 times more than those in sub-catchment II. And Those sediments were transported down to sub-catchment III by typhoon Mindulle. The results reveal sedimentation trend in sub-catchment I and II during Toraji, and incision trend in sub-catchment II and sediment deposition trend in sub-catchment III during Mindulle. (see Table 1) The impact of Chi-Chi earthquake is significant. It induced 4.28 times more landslides than before, and about 95% of the landslides are newly generated. For the landslides in those three sub-catchments, comparing with typhoon Mindulle, 150% more reactivated landslides and 10% less new landslides in sub-catchment I, 70% more reactivated landslides and 30% more new landslides

in sub-catchment II, 150% more reactivated landslides and 10% less new landslides in sub-catchment III were generated by Toraji. (see Table 2) The results show strong correlation between the catch sedimentation and landslides.

Table 1 Sedimentation in Wu River Catchment after the 1999 Chi-Chi Earthquake

Event	Section	Sedimentation (m^3)	
		Sediment generated	**Sediment accumulated**
Typhoon Toraji	**I**	**2,123,700**	**2,078,296**
	II	**776,100**	**746,747**
	III	**482,600**	**25,268**
	Total	**3,382,400**	**2,850,311**
Typhoon Mindulle	**I**	**404,600**	**323,243**
	II	**86,800**	**-36,890**
	III	**88,200**	**256,371**
	Total	**579,600**	**542,725**

Table 2 Landslide Inventory in Wu River Catchment for the Chi-Chi Earthquake and Following Typhoons

Event	**Section**	**Landslide Area (m^2)**		
		Reactivated	**Newly generated**	**Total**
Chi-Chi Earthquake	**I**	**1,434,512**	**9,757,293**	**11,191,805**
	II	**68,007**	**7,412,863**	**7,480,870**
	III	**149,036**	**12,945,831**	**13,094,866**
	Total	**1,651,555**	**30,115,986**	**31,767,541**
Typhoon Toraji	**I**	**6,479,725**	**4,457,230**	**10,936,955**
	II	**2,677,709**	**2,776,285**	**5,453,994**
	III	**1,699,019**	**1,788,833**	**3,487,852**
	Total	**10,856,453**	**9,022,349**	**19,878,802**
Typhoon Mindulle	**I**	**2,570,966**	**4,927,657**	**7,498,622**
	II	**1,560,172**	**2,098,742**	**3,658,914**
	III	**685,370**	**2,017,668**	**2,703,038**
	Total	**4,816,507**	**9,044,067**	**13,860,574**

However, the impacts of Chi-Chi earthquake on different sub-catchments are different. The landslides are more prone to reactivation during Toraji, especially in sub-catchment I; more prone to new generation during Mindulle, especially in the sub-catchment I and III.

The effect of topographic amplification could play an important role on the concentration of earthquake-induced landslides in segment I. Since the reactivated Chelungpu fault of Chi-Chi earthquake is actually closer to segment III instead of segment I. The significant increasing of reactivated landslides after the Chi-Chi earthquake could be due to the removal of woody plant or the deep damage of rock slopes. It also means that the tremendous amount of earthquake induced landslides are prone to be reactivated by the subsequent typhoon events, since it may take several decades to recover from the long term impact of Chi-Chi earthquake.

Since the self-healing effect continues to affect Ta-Chia catchment after Chi-Chi earthquake, it is reasonable to have a decreasing reactivated landslide area from Toraji (2001) to Mindulle (2004). However, the higher cumulative rainfall and rainfall intensity of Mindulle could be the main reason for the increasing of new landslides. In other words, landsliding during Toraji is more affected by Chi-Chi earthquake, this effect is decreasing with time. And the increasing of new landslides by Mindulle is because of its comparatively heavier rainfall.

Correlation of catchment sedimentation and landslides

1. Analysis of I_P

Based on the conceptual model, the I_P was analyzed and investigated by ArcGIS and statistic software SPSS for typhoons Toraji and Mindulle (see Figs. 3-4). It reveals that the sediment production decreased in the segment II (Nankang sub-catchment) during Mindulle which is consistent with the less rainfall in this segment. On the other hand, the sediment generation in segment I (Peikang sub-catchment) increased during Mindulle, due to the heavier rainfall in this area. The sediment production in segment III also slightly decreased during Mindulle.

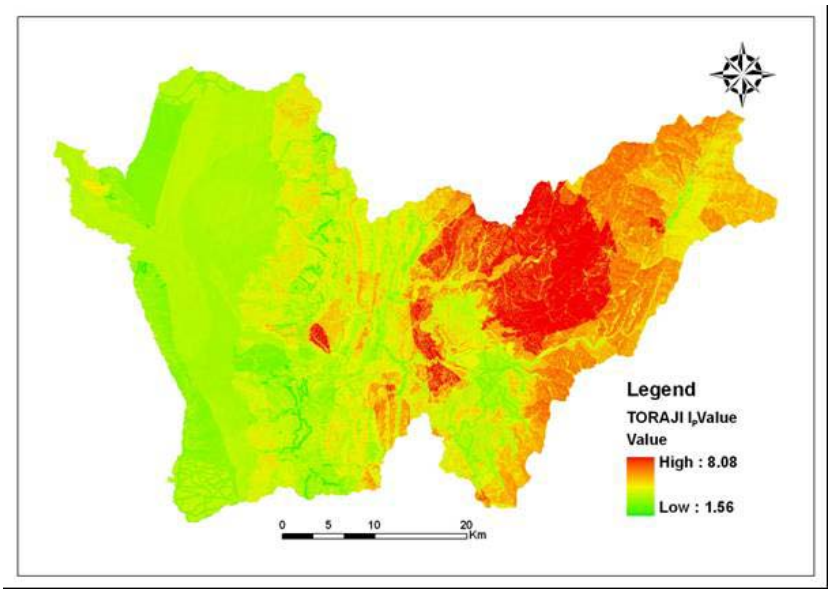

Fig. 3 Distribution of sediment generation index I_p for Typhoon Toraji (2001)

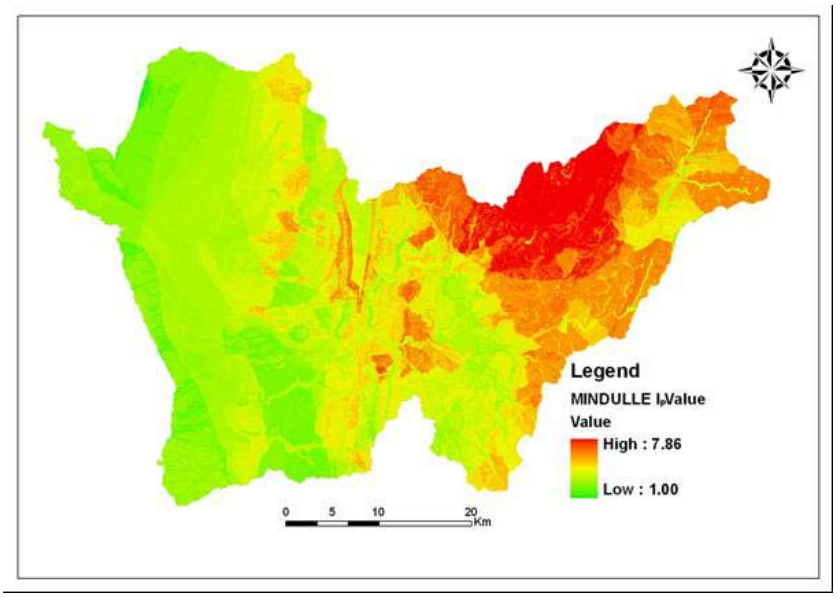

Fig. 4 Distribution of sediment generation index I_p for Typhoon Mindulle (2004)

Since the I_P is obviously related to landslide, it is also influenced by topography, rainfall, earthquake, and self-healing. The higher I_P distributions in segment I during Toraji and Mindulle are mainly due to the higher cumulative rainfall and landslide concentration in this segment. However, comparing with the I_P distribution of Toraji, the higher I_P of Mindulle is concentrated more in the main stream, which is consistent with the local behavior of sedimentation. The Chi-Chi earthquake induced sediments were transported from the branches to the main stream, and these sediments were deposited near the main stream waiting for transport.

2. Analysis of I_R

Similarly, the I_R was analyzed and investigated by ArcGIS and SPSS for typhoons Herb, Toraji and Mindulle (see Figs. 5-6). The results reveal a trend of sediment deposition in the main streams of segment I and segment II (higher I_R value) and in the segment III during Typhoon Toraji. And these trends in segment I and segment II were reversed by Typhoon Mindulle. Comparing the I_R distribution for Toraji and Mindulle, we can also find that the higher values of I_R is migrating from the upstream branches to the main stream and from upstream to downstream in segment II. In other words, the main stream of segment I and segment II is getting stable.

Since the I_R is closely related to the capacity of sediment transportation, it is affected by river morphology, sediment deposition and the landslide in the catchment unit. In comparison with

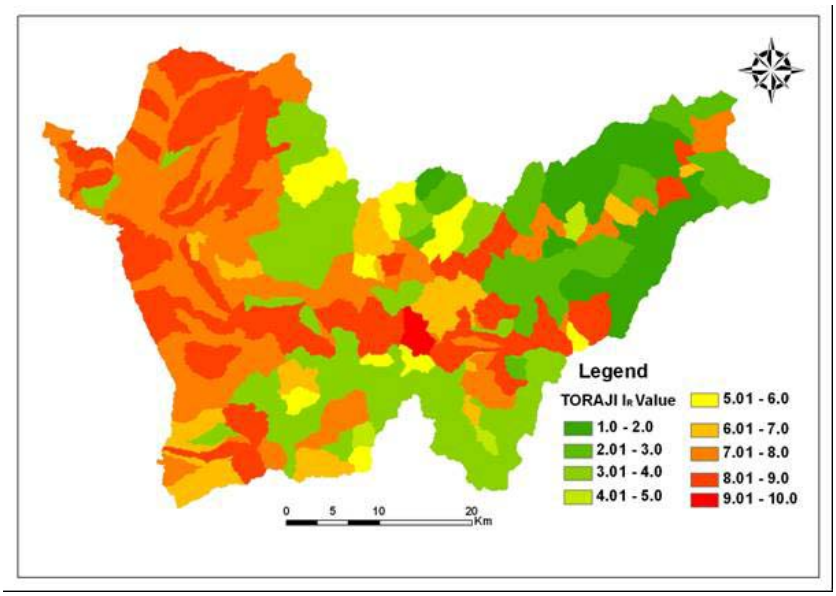

Fig. 5 Distribution of sediment generation index I_R for Typhoon Toraji (2001)

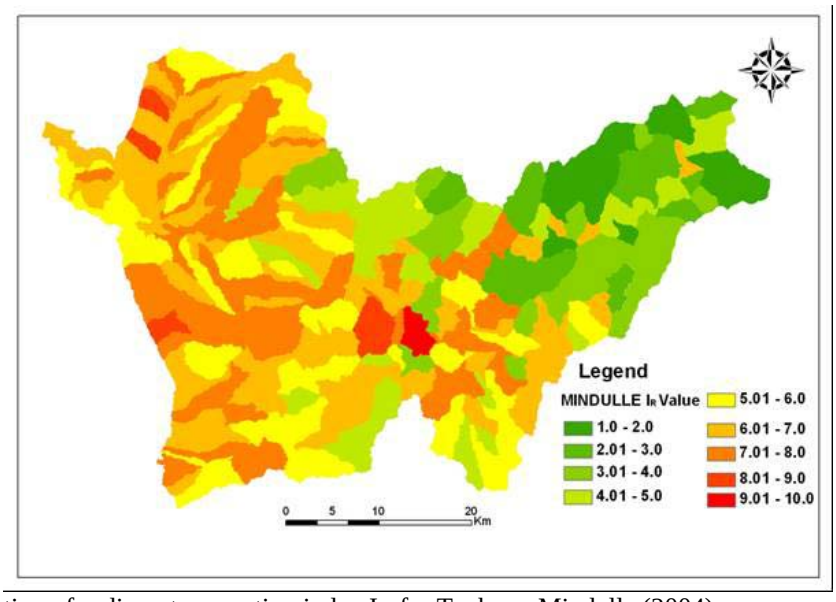

Fig. 6 Distribution of sediment generation index I_R for Typhoon Mindulle (2004)

Typhoon Toraji, the decreasing I_R distribution of Typhoon Mindulle seems consistent with the decaying impact of Chi-Chi earthquake. Nevertheless, due to the temporary self-healing effect, it is very possible that the topography was gradually recovered by the removal of surface colluviums after Chi-Chi earthquake. The higher IR distribution in segment II is caused by the insufficient sediment transport capacity, which is influenced by the landslides and sediments in the lower sector of segment II (in the Puli basin). Typhoon Mindulle brought heavy rainfall and triggered more landslides in the upstream, and those two factors have opposite correlations with I_R. This could be the reason why the IR was only slightly decreased in segment III. The heavy rainfall of Typhoon Mindulle also significantly decreased the I_R in the upstream sectors of segment I and segment II. It also reflects the changing from deposition to incision.

CONCLUSIONS

Considering variation in topography, geology, flow discharge and sediment discharge, the Wu River catchment is divided to three segments, the Peikang sub-catchment (I), Nankang sub-catchment (II), and mid to lower stream of Wu River (III), for the analyses. In order to investigate the impact of the 1999 Chi-Chi earthquake, two typhoon events, i.e., Toraji (2001) and Mindulle(2004) were adopted. Landslide inventory and catchment sedimentation analysis results were obtained and analyzed, then the correlation of catchment sedimentation and landslides was studied. A conceptual model based on equilibrium of sediment in s sub-watershed was derived and applied for the analysis of correlation between the sedimentation and control factors.

The correlation study suggests that landsliding is critical for sediment generation and sediment transportation in the Wu River catchment. Its influence is stronger after the Chi-Chi earthquake, and decreases gradually. The sediment transportation is intrinsically related to landslides, since it is closely related to the river morphology, which is frequently affected by landsliding. The results also suggest that the stability of landslides and sediments in segment I is critical for the stability of Wu River catchment.

ACKNOWLEDGEMENTS

This research was made possible by the financial support of the Central Geology Survey of Taiwan (Project No. 98-5826901000-05). We appreciate the databases and support from the research groups carrying out the other subsidiary projects, including Sinotech Engineering Consultants, Disaster Prevention Research Center of National Cheng-Kung University, and GAIAS GIS Consultant Co.

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