Sediment Budget at Wushihkeng Watershed after Chi-Chi Earthquake

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Abstract

On 21th September 1999, Wushihkeng watershed was suffered a severe raid from Chi-Chi earthquake, and plenty of geohazards, like slope failures and landslides, were triggered by such an event. A large volume of unstable sediments were transported to downstream and deposited on riverbeds. According to fieldwork result, the thickness of deposition was more than 10 meters, and the environment was changed rapidly. This research applies fieldwork surveillance, GIS and Remote Sensing in studying the process of sediment budget at Wushihkeng watershed. The mechanism of sediment yielding can be divided into three parts, slope failure, landslide and soil erosion. Satellite images (SPOT and FORMOSAT-2) and GIS are applied to map geohazards. And USLE formula is used to calculate the volume of soil erosion. Mass conservation is the main conception in this research which analyzes the sediment budget in the watershed, and the process of residual sediments and the enlargement of bared slopes at Wushihkeng watershed are also discussed in the article. The result demonstrates that the condition of slope failures and landslides is getting stable in the two branches, Tangshanliau and Chitungliau. In these two areas, residual sediments have been transported to the main stream, and no debris flows have been triggered since 2004. However, the main stream and one of its branches, Kanhsi, are still suffered severe raids from debris flows, and the thickness of deposition is getting higher ceaselessly. The reason for this is that the bared slopes are enlarged after each heavy storm, and there are still numerous residual sediments accumulated on the riverbed. After comparing the result of sediment budget analysis and the result of fieldwork measurement, the variation is only about 2%. The result demonstrates that sediments budget model gets a good result in analyzing the process of sediments at Wushihkeng watershed, and explains the different condition of mass movement at its branches.

Keywords: it Earthquake, Watershed, Sediment Budget, Remote Sensing

Introduction

On 21st September 1999, Da-An river watershed, where several faults are located, was suffered from a severe damage by Chi-Chi earthquake. In such event, plenty of landslides were triggered and had a great impact to the local sediment condition which became unstable. Wushihkeng (Fig.1), located in Taichung county, is a main subbasin of Da-An River midstream. Wushihkeng village, located in the confluence of the mainstream and Da-An River, is the main area of human activities. Because of the impact of the earthquake, now, Wushihkeng is declared as the potential dangerous stream of debris flow by the Soil and Water Conservation Bureau, Taiwan.

Due to the geohazards frequently happened in Wushihkeng watershed, landslides and debris flows were easily seen whenever heavy rainfall and typhoons came. For this reason, the process of sediment transporting and depositing is a very important factor for researchers or government to investigate. However, in the past, the analysis of sediment process needed lots of money and time consuming. The technique of remote sensing, recently, has been well developed and is suitable for surveillance, and GIS system is also well upgraded for analyzing. Further, the combination of RS and GIS can provide large scale investigation and long term analysis for researchers to conduct their researches, and it reduced the actual cost of analysis. In this research, RS and GIS techniques are applied to simulate the sediment process, named sediment budget, of Wushihkeng

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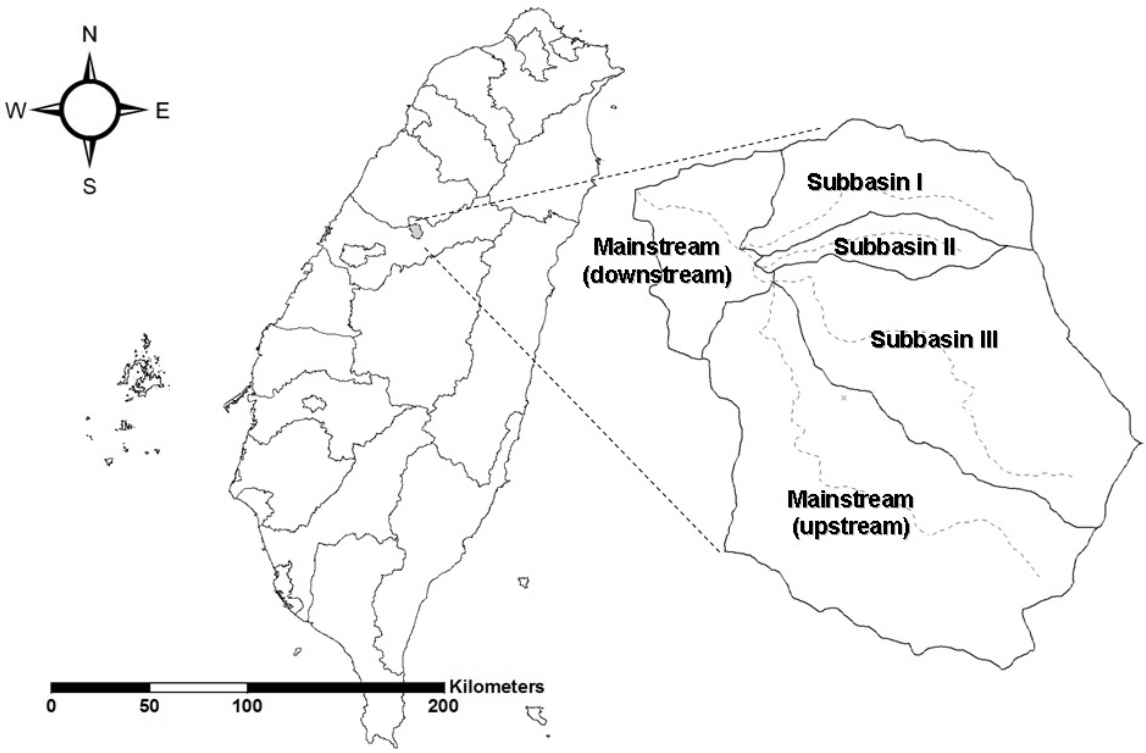

Fig. 1. The location of Wushihkeng watershed in Taiwan

watershed. Mass conservation, which is also introduced in this paper, is the main concept of sediment budget. Finally, the result of analysis is verified through fieldwork measurement.

Information and Hazard Histories of Watershed

The area of Wushihkeng watershed is about 3,456 hectares, and the watershed which is greater than 15 degrees is about 2,100 hectares. The topographic characteristic here is great fluctuations in the slope. Besides, the geological condition is weak because of several faults are located in the watershed, and sediment materials are easily yielded in this kind of highly disturbing area. Another weak condition is that the river banks are mainly consisted of alluvium, which is easily erodible by runoffs. Both of the conditions make the materials generated quickly. According to the record, the precipitation here is about 2600∼3100 millimeters per year, and almost 70% of rainfall are falling down between May and September. Such special geological and hydrological conditions provide great opportunities for sediment process.

Except for the mainstream, there are three major substreams in Wushihkeng watershed : Tanshanliao (Subbasin-I), Chitungliao (Subbasin-II) and Kanhsi (Subbasin-III). All of these substreams are declared as potential dangerous streams of debris flow, and several hazards were found after the earthquake. The detail of the area, stream length, mean slope of stream and geology of these substreams are listed below (Table 1). From this table, the mean slopes of stream in all substreams are over 10 degrees, and this indicates that debris flow will be easily triggered if enough sediments and water are supplied. The most difference of each subbasin is geology. The major components of Subbasin-I and Subbasin-II are Grit and Shale, but Subbasin-III and upstream of mainstream are Graywacke, Shale and Metamorphic Rock. Such different geological conditions have a great impact for sediment process.

After the earthquake, sediment hazards are happened whenever rainy seasons come. The situations in the first year after earthquake was the most serious: four debris flows were triggered. After then, four serious hazards were triggered, and the dates were 2001 (Tojari Typhoon), 2004 (Mindulle Typhoon and Aere Typhoon) and 2005 (Matsa Typhoon) respectively. All engineering structures were damaged by debris flows, and the stream bed was raised up more than 10 meters. The original landforms were changed quickly. The history of debris flows in Wushihkeng watershed is presented below (Table 2). From the table, we can find that the critical precipitation of debris flow is getting lower suddenly because of the earthquake, but the tendency moves upward after that. The lowest precipitation of debris flow was only 150 millimeters in 2000. In 2001, the

Table 1. Basic information of Wushihkeng watershed

	Area (ha)	Length (km)	Mean Slope of Stream (degree)	Geology
Mainstream (Downstream)	1757	9.7	8.2	Grit, Shale
Mainstream (Upstream)				Graywacke, Shale, Metamorphic Rock
Subbasin I	443	4.1	12.5	Grit, Shale
Subbasin II	172	2.8	10.7	Grit, Shale
Subbasin III	1085	6.7	13.7	Graywacke, Shale, Metamorphic Rock

Table 2. History of debris flows in Wushihkeng watershed

	Event	Rainfall (mm)	Position
2000.2.21 - 2.22	Normal Rainfall	243	All Subbasins
2000.4.22 - 4.23	Normal Rainfall	154	All Subbasins
2000.4.28 - 4.29	Normal Rainfall	203	All Subbasins
2000.6.13 - 6.14	Normal Rainfall	306	All Subbasins
2001.7.28 - 7.31	Toraji Typhoon	418	All Subbasins
2004.6.30 - 7.05	Mindulle Typhoon	1657	Besides Subbasin-II
2004.8.23 - 8.26	Aere Typhoon	1225	Besides Subbasin-II
2005.8.03 - 8.06	Matsa Typhoon	980	Besides Subbasin-I & II

lowest precipitation was up to 400 millimeters. In 2005, the lowest precipitation was raised to 1000 millimeters already. The symptom points out the criteria of debris flow changed with time. Additionally, the locations of debris flow were changed with time too. In 2001, because of well supplied unstable sediments, debris flows were occurred in each subbasin and the mainstream. Since 2004, debris flow has not ever been occurred in Subbasin-II. In 2005, Subbasin-III and upstream of the mainstream were still suffered from the damage of debris flows during Matsa Typhoon, but Subbasin-I and Subbasin-II were not at the same time. The spatial difference showed that the sediment process would not be the same because of different geological and sediment conditions.

Sediment Yielding in Wushihkeng watershed

The resource of sediment can be divided into three main parts: landslide, soil erosion and failure of stream bank. Seven remote sensing images are selected, one before the earthquake and six after the earthquake, and the method of variable point was developed to analyze landslides and failure of stream bank. For satellite images, the potential area of landslides is marked through comparing the value of NDVI in a pair images. Besides, USLE formula is also applied to analyze the amount of soil erosion.

However, the variable point of NDVI can not be presented as true landslides because of poor discrimination and advanced analysis and fieldwork must be preceded. In this research, four types of landuses are filtered out from the potential area of landslides: stream, road, infield and villages. The streams are filtered by GIS layers, which are built by automatic analyzing with digital elevation model. The roads are filtered by features provided by Taiwan Ministry of the Interior. Further, fieldworks, in order to filter out the infield and villages, were proceded, and also checked the result of landslides. After determinating the potential areas of landslides, the exact position of landslides could be found. Finally, the variation of landslides can be realized through comparing images.

Fig.2 presents the variation of landslides. From Fig.2, we can easily find that the landslide areas were about 49.9 hectares before earthquake, and the accumulative avalanche rate was only 1.4%. The major area of landslides was located in upstream of the mainstream and Subbasin-III, where most areas were slope failures

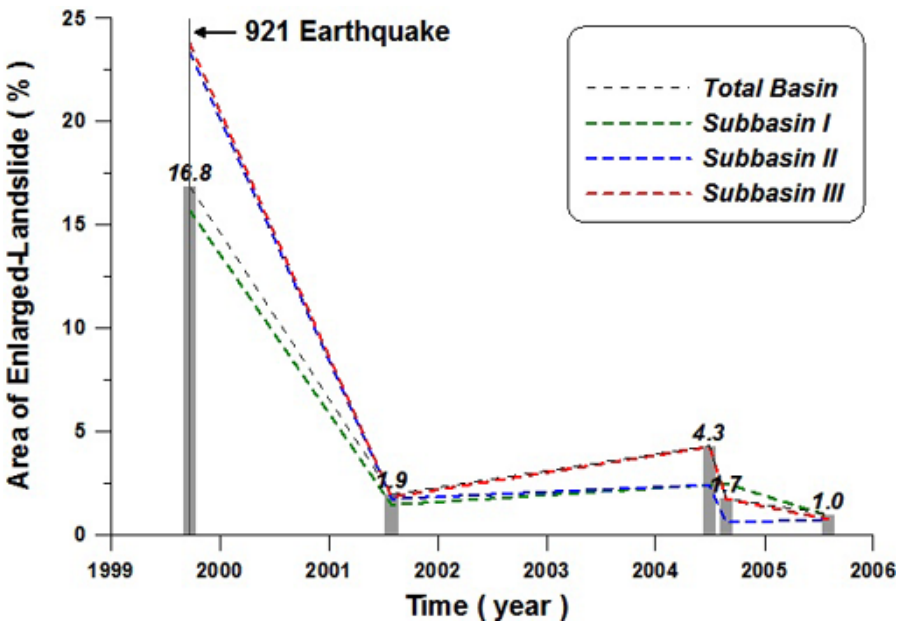

Fig. 2. Variation of landslides in Wushihkeng watershed

with small scale. After earthquake, there were landslides everywhere in basins. The enlarged landslide areas were about 582 hectares, and the augmentative avalanche rate was 16.8%. Except for slope failures, there were several landslides in upstream of each subbasin and mainstream. Plenty of sediments were yielded by both slope failures and landslides. After then, because of heavy rainfall and typhoon, the sediments were increased due to enlargement of landslide, erosion of deposits and failures of stream banks, which provide well condition to trigger mass movements.

We can also find that the earthquake is the most important impact factor to sediment yielding from the Fig.2. Between 2000 and 2004, landslides were not obviously enlarged because rainfalls were not big enough to enlarge landslides. Only a few of landslides were slightly enlarged by Toraji Typhoon, in 2001. The augmentative avalanche rate was only 1.9%. The enlargement of landslide was apparent in 2004 because of severe precipitation supplied by Mindulle Typhoon and Aere Typhoon, which has about 1657 and 1225 millimeters in the amount of precipitation respectively. Besides, enlarged landslide rate is 4.3% and 1.7% during these two typhoons (Fig.3 presents the landslides distribution after Aere Typhoon). However, in 2005, the enlargement of landslide was insignificant again. The variation of landslides in all subbasins was presented in the figure above. The same tendency is also appeared in each subbasin. On the contrary, the variation of landslide Subbasin-I and Subbasin-II were not obvious after the earthquake. Most enlarged locations were generated by failure of stream banks with runoffs, and the bare slopes were getting stable after the earthquake. The situation is quite different from the mainstream and Subbasin-III, and the sediments process would be different in these 2 groups.

The amount of generated sediments was calculated by product of enlarged landslides and thickness of landslides. The thickness of landslide can be acquired by fieldworks. The results show that the thickness of slope failure is about 1.0 $\sim$ 1.5 meters only, and the thickness of landslides, especially in the mainstream and Subbasin-III is about 1.5 $\sim$ 2.0 meters.

USLE formula is chosen to estimate yearly soil erosions in this paper. The Wushihkeng watershed is divided into 49 subbasins according to geological characteristics and soil erosions is calculated in each subbasin. Estimating the parameters of USLE is one of the most important works. The rainfall-runoff erosive indices and soil erodibility factor can be determined by Wischmerier and Smith's formula. Slope length factor and steepness factor can be acquired by USLE, and cover-management factor can be got by landuses from fieldworks and remote sensing images. The result of USLE shows that the total soil erosion of whole watershed is about 300 thousand stere. Most erosions are yielded at the mainstream and Subbasin-III, and the amount is 4. 3 and 1.9 thousand stere respectively.

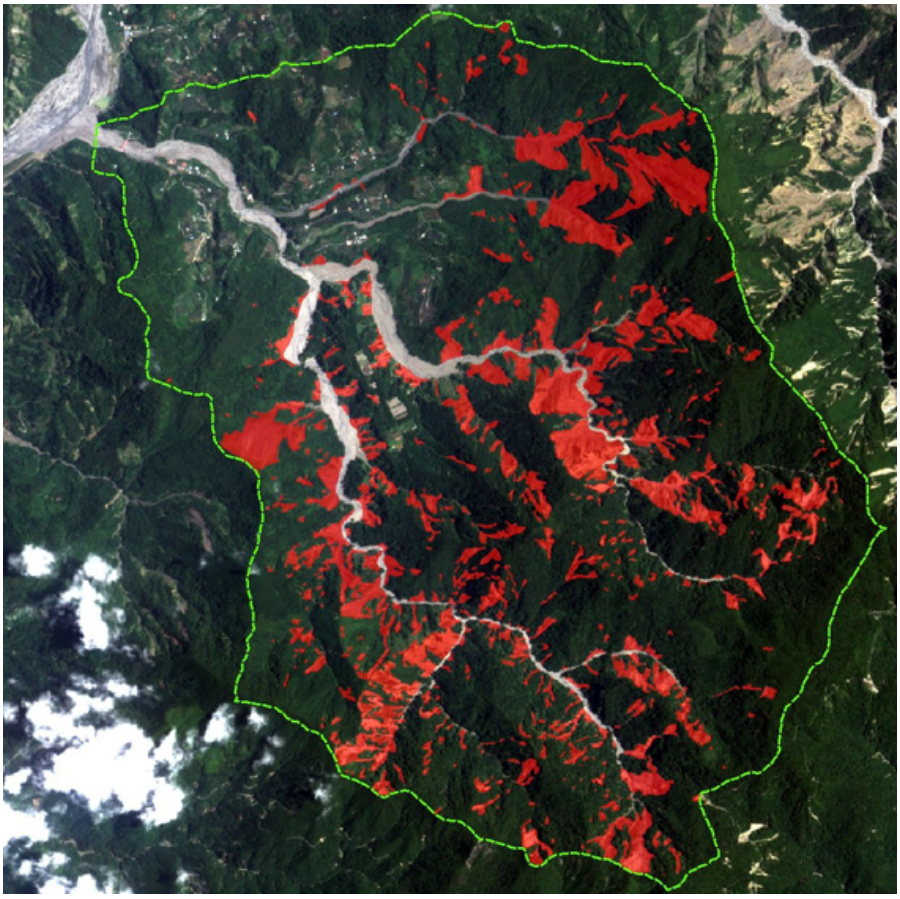

Fig. 3. Position of landslides after Aere Typhoon in 2004

Sediment Transportation in Wushihkeng watershed

The analysis of sediment transportation includes the sediment discharge at confluence of substreams and mainstream. Not only the rainfall events which triggered debris flows are chosen, but also joins in the significant rainfall events in each year. Further, unit hydrograph was calculated to derive the discharge at confluence. Finally, the equilibrium concentration formula is applied to transform the runoffs to sediment discharge

The equilibrium concentration formula was developed by Shieh and Tsai in 1997. They completed this regress formula by applying the experiment data from Ashida, Takahashi and Mizuyama. This formula can be assigned by slope of river bed, and its limitation is the slope under 25 degrees, that means it can describe any kind of sediment movement, including bed loads and debris flow. The equilibrium concentration formula (Eq.1) and the results of sediment discharge (from confluence of mainstream and Da-An River) are attached below (Table 3).

$$C_\infty = \exp(1.73 \cdot \ln\theta - 5.83) \tag{1}$$

where C_∞ is equilibrium (volume) concentration, and θ is the bed slope.

Sediment Budget

Summary the above results of sediment yielding and transportation, the process of sediment budget in Wushihkeng watershed can be estimated. The main idea of sediment budget is mass conservation, and the watershed could be divided into several subbasins (Fig.5). Sediments yielding from slope in subbasins are transported to the mainstream, and then flow out the confluence. The time interval of computation began in 2000 and ended in 2005. The source of sediments is calculated from landslides and soil erosions by remote sensing images and USLE formula respectively. Further, the sediments discharge is calculated from the

Table 3. Results of sediment transportation after earthquake at Wushihkeng watershed

	Event	Precipitation	Transported Sediments
2000.0426 ~ 0502	Plum Rains	447	249
2000.0610 ~ 0613	Plum Rains	342	190
2001.0518 ~ 0523	Plum Rains	378	211
2001.0729 ~ 0730	Toraji Typhoon	418	233
2001.0916 ~ 0918	Nari Typhoon	296	165
2002.0703 ~ 0704	Rammasun Typhoon	302	168
2002.0710 ~ 0712	Nakri Typhoon	231	129
2003.0607 ~ 0612	Plum Rains	531	296
2004.0701 ~ 0705	Mindulle Typhoon	1657	924
2004.0823 ~ 0825	Aere Typhoon	1225	683
2005.0612 ~ 0619	Storm	289	161
2005.0716 ~ 0720	Haitang Typhoon	581	324
2005.0803 ~ 0806	Matsa Typhoon	980	546
2005.0830 ~ 0901	Talim Typhoon	200	111

Unit : Precipitation (millimeters) ; Transported Sediments (Thousand Stere)

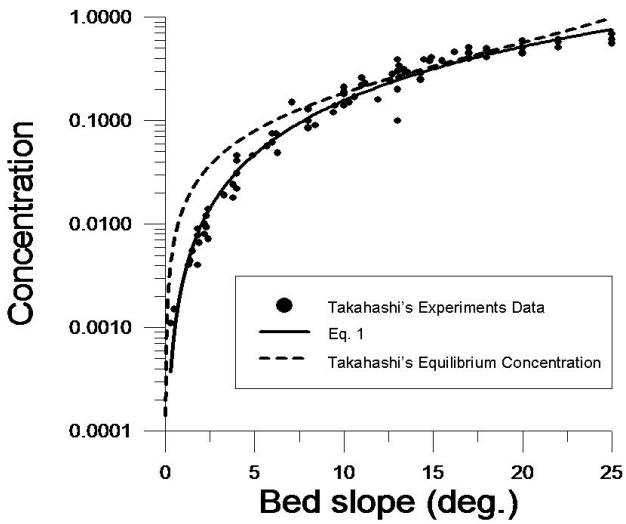

Fig. 4. The equilibrium concentration formula by Shieh and Tsai (1997)

equilibrium concentration formula. Table 4 presents all the phenomenons and equations (or methods) which are used in the analysis of sediment budget.

According to conception of mass conservation, the remnant sediments at watershed can be estimate by this equation:

- Sediment yielding in mainstream + Sediment yielding in subbasins − Sediment discharge through confluence = Remnant Sediments

By applying methods mentioned above, the process of sediment budgets can be calculated year by year, and the amount of remnant sediments, generation and discharge are concluded as hydrographs.

Fig.6 shows the result of the whole watershed, and the remnant sediments in the whole basin are 6.1 million stere in 2005. Most of the remnant sediments were yielded by landslides which were triggered by the earthquake in 1999, and the amount were about 4.4 million stere in that moment. Residual were almost generated during Mindulle typhoon and Aere typhoon which totally brought the rainfall in about 3000 millimeters. After the earthquake, the dynamic balance between sediment yielding and transporting is well developed. However, the heavy typhoons, in 2004, broke this dynamic balance and increased the remnant sediments in the watershed.

In order to discuss the process of sediment budget in detail in subbasins, the same methods were applied

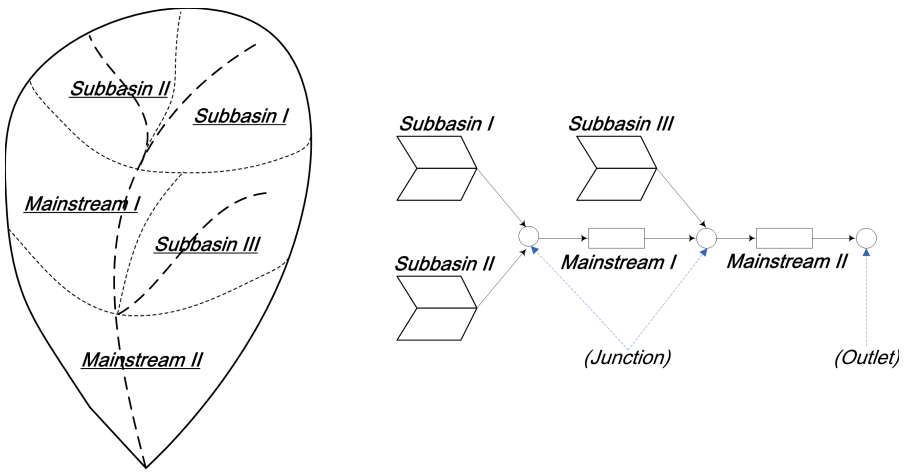

Fig. 5. Subbasin systems of sediment budget

Table 4. Equations or methods for computation of sediment budget

Phenomenon		Equations or Methods
Sediment Yield	Soil Erosion	USLE
	Shallow Landslide	Ranged by Remote Sensing
Sediment Transportation	Runoff	Unit Hydrograph
	Sediment Transpotation	Equilibratory Concentration Equation

(Fig.7–Fig.9). We can clear find that the amount of remnant sediments in Subbasin-III are the largest which are about 1.9 million stere in end of 2005. The second place is Subbasin-I, which is about 0.2 million stere, and Subbasin-II is only 0.1 million stere. The remnant sediments in Subbasin-III are slightly decreased after earthquake, but sediment generation, in 2004, was filled up the decrement. Therefore, the remnant sediments in Subbasin-III were not changed appreciably after the earthquake. On the contrary, the remnant sediments in Subbasin-I and Subbasin-II were gradually decreased year by year. That's because the bare slopes were stable after earthquake in these 2 subbasins. The new materials in these two subbasins were not sufficient as in Subbasin-III. Furthermore, the transported sediments in these two subbasins are greater than generated ones, and most of sediments were transported to the mainstream during these 5 years. In the case, there are no severe debris flows in these 2 subbasins since 2004, but mainstream and Subbasin-III were still suffered from debris flows. Eventually, the remnant sediments in these 2 subbasins are getting stable than the others.

In addition, in order to verify the result of sediment budget, measurement in the field was conducted three times: one was after Toraji Typhoon in 2001, another was after Aere Typhoon in 2004 and the other was after Longwang Typhoon in 2005. The electronic total station, modeled GPT-8200 by Topcon, was used to measure the stream. There are two modes in GPT-8200, prism and non-prism total station, which improves the lack of traditional measurement with prisms. The visibility can be measured easily because of non-prism mode, even if inapproachable places and the cost of measurement can be decreased efficiently. The result of measurement would be compared in a pair, and the variation of remnant sediment can be calculated by GIS tools. According to the result, the stream bed was raised quickly after earthquake, and the elevation has been raised up more than 10 meters since earthquake. Finally comparing the results of measurement and sediment budget, the error is only 2%. The result shows that the sediment budget gets good result in simulating the process of sediment movement.

Conclusion

Because of Chi-Chi earthquake, a plenty of sediments were yielded in Wushihkeng watershed and triggered mass movement unceasingly. In order to realize the process of sediment budget in Wushihkeng, remote sensing images and USLE formula are both applied to calculate the sediment generation of landslides

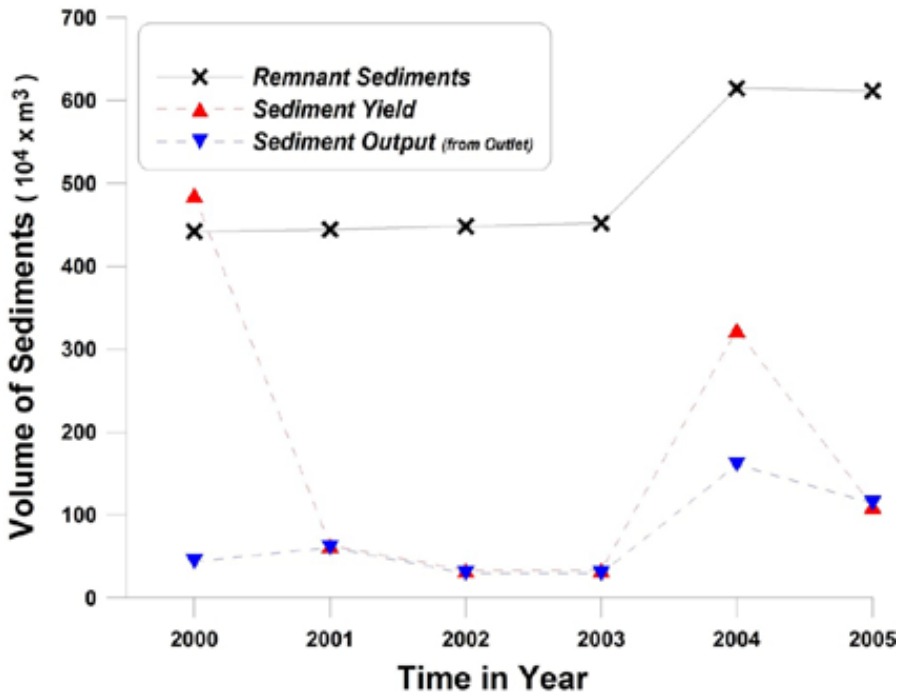

Fig. 6. Process of sediment budget in whole watershed

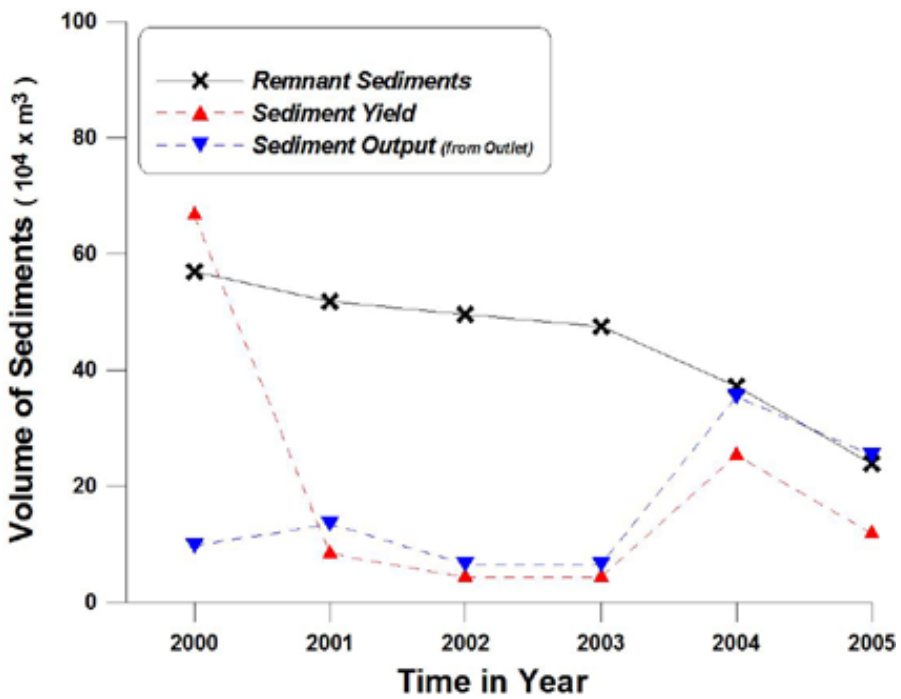

Fig. 7. Process of sediment budget in Subbasin-I

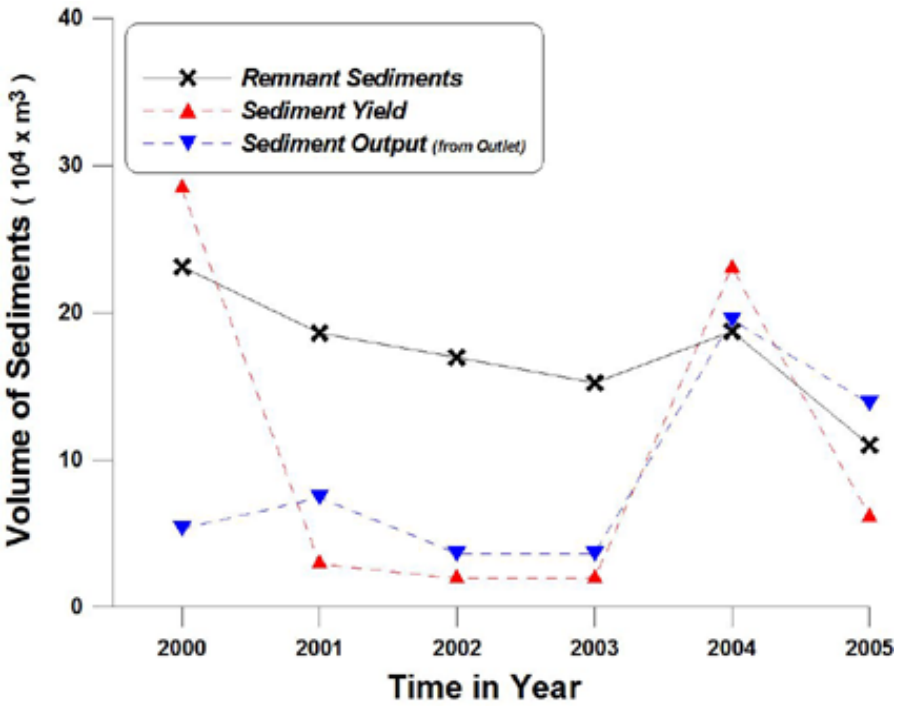

Fig. 8. Process of sediment budget at Subbasin-II

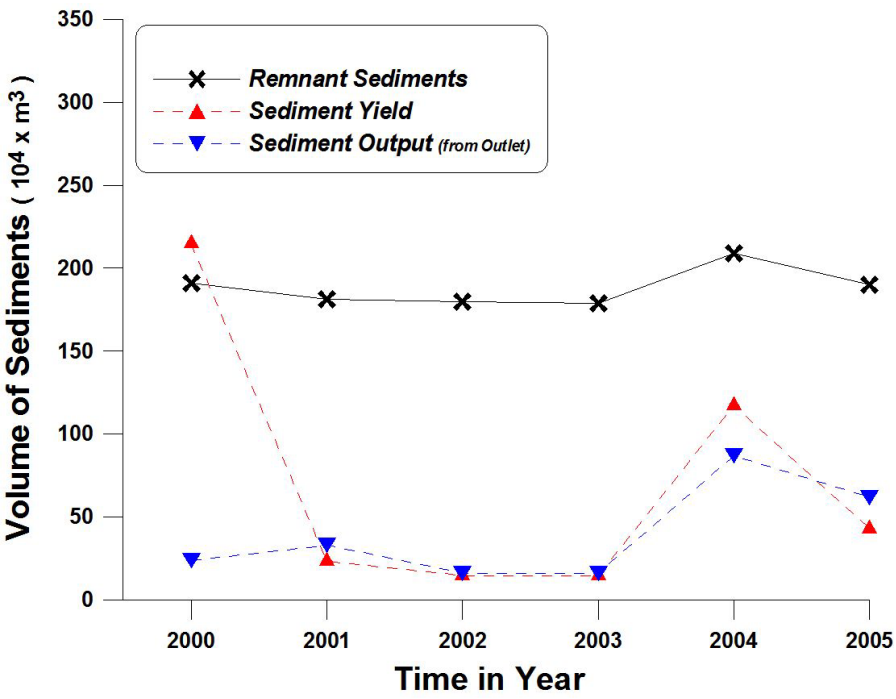

Fig. 9. Process of sediment budget at Subbasin-III

and soil erosions. Besides, equilibrium concentration formula is derived to calculate the sediment discharge by runoffs. Mass conservation is the major idea to develop the process of sediment budget. The result shows that most of sediments in Wushihkeng were generated by landslides and slope failures which were triggered by the earthquake and the amount were approximately about 4.4 million stere. After that, the remnant sediments were not decreased quickly because of the lack of rough typhoons, and dynamic balance between sediment yielding and transporting. In 2004, Mindulle and Aere Typhoons broke this balance and brought about 3000 millimeters precipitation in this area. Landslide, slope failure, and failure of stream bank were triggered at the same time. New generated materials made the amount of sediment increased, totally about 6 million stere, and the elevation of stream bed was raised up more than 10 meters. The original landforms were damaged by such events.

Because of different geological and sediment conditions, each subbasin has different process of sediment budget. The majority of Subbasin-I and Subbasin-II, which are mainly consisted of Grit and Shale, are stable since 2004 because of stabilities of bare areas, and only a few stream banks are suffered eroding. In the case, the remnant sediments are decreased year by year, and most materials are transported to the mainstream. Further, debris flows were not triggered since 2004 either. On the contrary, Subbasin-III and upstream of the mainstream, which are consist of Graywacke, Shale and Metamorphic Rock, were still suffered severe eroding until 2005. The remnant sediments are not decreased because of ceaseless generation of sediments. Such an event changes the landforms and proves that different geologic conditions result in different sediment processes.

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