# DEBRIS FLOWS:
# Disasters, Risk, Forecast, Protection

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S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva

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# 泥石流：
# 灾害、风险、预测、防治

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Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

# Effects of structure conservation implementation on landslide and debris flow hazards: A case study in Chenyulan watershed, Taiwan

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**Abstract.** In this study, the records of landslide and debris flow hazards were collected from 1996 to 2022 in Chenyulan watershed in Nantou County, central Taiwan. The data of engineering conservation, such as engineering structures, costs, locations, contents, creeks remediation and landslide improvements, etc., was collected by the engineering system of SWCB (Soil and Water Conservation Bureau, Taiwan) between 1998 and 2022. The satellite images and aerial photographs were collected to compare the variations of debris flow deposited areas and the areas of landslides after heavy rainfalls and Chi-Chi earthquake in Chenyulan watershed from 1996 to 2022. In addition to the representative rainfall events, the suspended sediment discharges in downstream of the watershed were collected from 1972 to 2022 for further verifying the variations after variations of rainfalls and conservation implementation. The relationship among the variations of debris flows and the areas of landslide events were analyzed. The characteristics of each effective rainfall and the yearly costs of engineering conservation were analyzed as well. The analyzed results show that the yearly costs of engineering conservation after Chi-Chi earthquake within 5 years was higher than the other periods, and the frequency of debris flow events, landslides and the river suspended sediment discharges were higher than the other periods too. The yearly costs of engineering conservation, the frequency of debris flow events, landslide areas and the river suspended sediment discharges gradually decreased in the last decade. The causes of decreasing costs of engineering conservation in the last decade are preliminarily analyzed as follows: 1. The hazards of debris flows and landslides have already declined, thus the required conservation treatments were decreased in the last decade. 2. The conservation engineering has been built in the creeks to trap the loose soil on slopes and prevent the sediments from running into rivers in the watershed caused by Chi-Chi earthquake and subsequent rainfall events. 3. The main conservation structures were completely established at the creeks with higher potential of debris flows and landslides in upstream; therefore, there are no more conservation requirements now; 4. The decline in suspended sediment discharges shows the conservation works have obviously controlled soil and adjusted slopes through the implementation of structure conservation in the watershed in the last decade.

***Key words:*** *Chenyulan watershed, conservation structures, debris flows, landslides, Chi-Chi earthquake*

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# Влияние инженерных мероприятий на опасность оползней и селей на примере бассейна Чэньюлан, Тайвань

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**Аннотация.** В этом исследовании собраны данные об опасностях оползней и селей с 1996 по 2022 г. в бассейне Чэньюлань в уезде Наньтоу (центральный Тайвань). Характеристики инженерных мероприятий (тип защитных сооружений, их стоимость, местоположение и т.д.) были собраны инженерной системой SWCB (Центр экологии почв и водосбережения, Тайвань) в период с 1998 по 2022 г. Использовались также спутниковые и аэрофотоснимки для сравнения изменений площадей селевых и оползневых отложений после сильных дождей и землетрясения Чи-Чи в бассейне Чэньюлань с 1996 по 2022 г. Проанализирована связь между вариациями селевых потоков и площадями оползневых событий. Также были проанализированы характеристики эффективного количества осадков и годовые затраты на инженерные мероприятия. Полученные результаты показывают, что ежегодные затраты на инженерную защиту после землетрясения Чи-Чи в течение 5 лет были выше, чем в другие периоды, как и частота селей, оползней и наносоводных паводков. Ежегодные затраты на инженерные мероприятия, частота селевых потоков, оползней и наносоводных паводков за последнее десятилетие постепенно снизились. Анализ причин снижения затрат на инженерные мероприятия в последнее десятилетие позволил сделать следующие выводы: 1) опасность селей и оползней уменьшилась, поэтому снизилась потребность в защитных мероприятиях. 2) в долинах ручьев были построены защитные сооружения для улавливания рыхлого материала со склонов, накопившегося после землетрясения Чи-Чи и последующих дождей, и предотвращения его попадания в реки бассейна; 3) основные защитные сооружения уже размещаются в долинах ручьев с повышенным риском формирования селей и оползней в верхнем течении, поэтому в настоящее время нет необходимости в дополнительной защите; 4) снижение стока взвешенных наносов свидетельствует о том, что уже реализованные меры показали свою эффективность.

***Ключевые слова:*** *бассейн Чэньюлань, инженерные сооружения, селевые потоки, оползни, землетрясение Чи-Чи*

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## Introduction

Taiwan island results from collision of the tectonic plate. It is famed for its young and weak geologic conditions, steep slopes, rugged mountains, and frequent earthquakes. All these factors above attribute to the process of the orogenesis. Besides, because Taiwan is on the migration path of typhoons, there are 3 to 4 typhoons striking Taiwan island each year. They usually bring high winds, torrential rainfalls and suddenly rising floods, and cause landslides, debris flows and soil loss. The Chenyoulan stream watershed, located in Nantou County in central Taiwan, has a catchment area of 449 km$^2$, a main stream length of 42 km, a mean stream gradient of 4°, and elevations between 295 and 3952 m. as shown in Fig. 1. The Chenyoulan stream follows the Chenyoulan Fault, a boundary fault dividing two major geological zones of Taiwan. In addition to the main boundary fault, the Chenyoulan stream watershed also contains many other faults accompanied by fracture zones, which indicated that the rock mass on the hillslopes was considerably fractured in the Chenyoulan stream watershed. Consequently, fractured rock masses prevail within the study area, accounting for enormous landslides and providing an abundant source of rock debris for debris flows and soil loss [*Lin and Jeng, 2000*]. The annual rainfall in the watershed ranges from 2000 mm to 5000 mm with an average value of approximately 3500 mm. Approximately 80% of the annual rainfall in the watershed occurs between May and October, especially during typhoons. Debris-flow and landslide hazards are common within the watershed due to the combination of weak geological conditions, heavy rainfall, and accompanying frequent earthquakes. Several debris-flow events in this watershed have been studied or documented [*Lin and Jeng, 2000; Chang et al., 2001; Cheng et al., 2005; Jan and Chen, 2005; Chen and Jan, 2008; Chen et al., 2009; Chen, 2011; Chen et al., 2011b*]. Besides the 1999 Chi-Chi earthquake with a moment magnitude $M_W$ =7.6, on September 21, 1999, was the largest in Taiwan for 70 yr and the largest on the Chelungpu thrust fault in 300–620 yr [*Shin and Teng, 2001, Chen et al., 2001, Dadson et al., 2004, Huang et al., 2001*] and it caused significant effects in the Chenyoulan watershed. After the Chi-Chi earthquake, the extremely heavy rains brought by Typhoon Toraji and Nali in 2001 caused numerous debris-flow and landslide events in central Taiwan [*Cheng et al., 2005*], and resulted in over 100 people dead or missing and destructive damage to houses, roads, bridges, and dikes. In August 2009, Typhoon Morakot brought heavy rainfall with an hourly rainfall up to 123 mm and a 48-h cumulative rainfall up to 2361 mm, as measured at Alisan rainfall station. It caused many debris-flows, landslides and other destructions. Based on the safety of people property and soil disaster prevention, the Taiwan government has invested a large amount money to carry out conservation projects for creeks and to control soil loss in the Chenyoulan watershed.

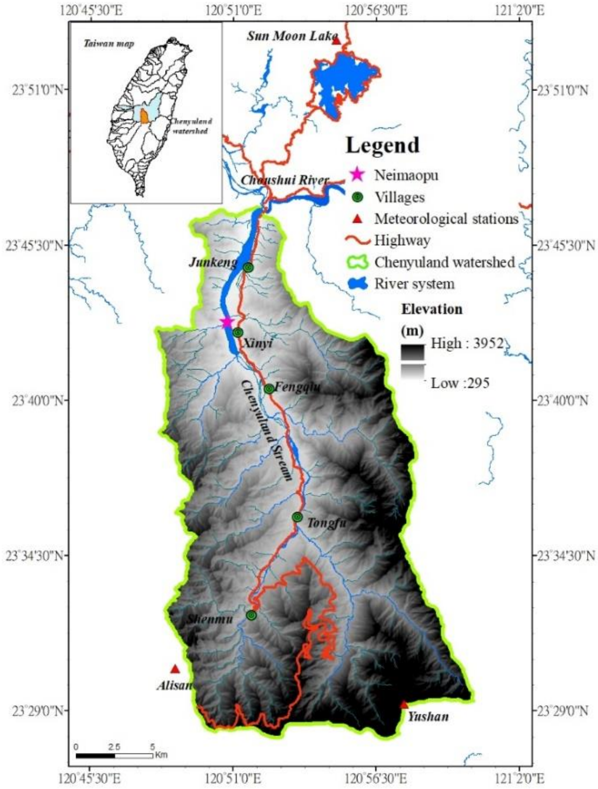


Fig. 1. Locations of Neimaopu and meteorological stations in Chenyulan stream watershed

This study utilized hydroclimatic data of rainfall events triggering debris flows from 1985 to the end of 2019. These debris-flow and landslide events, triggered by rainstorms and typhoons between 1985 and 2019, along with the collection of rivers suspended sediment discharges at downstream of Chenyoulan stream, provide an opportunity to study the variability in the number of specified rainfall events and costs of engineering conservation associated with the variations of suspended sediment discharges in the last decades in the Chenyoulan stream watershed.

Therefore, this study aims to explore: 1. The impact of long-term rainfall variability on debris-flow and landslide disasters in Chenyoulan stream watershed. 2. Changes in debris-flows and landslides after extreme rainfall variability, as well as the investment amount of SWCB in the last decades. 3. Changes in downstream suspended sediment discharges after SWCB investment. 4. Clarify the impacts of rainfall changes and engineering conservation on downstream suspended sediment discharges.

## Rainfall events in the study area

Jan and Lee (2004) suggested an estimating method of rainfall that is Neihaus suitable to assess the debris-flow and landslide occurrences, especially concerning the pattern of continuous and concentrated rainfall events. For triggering debris-flow and landslide occurrences, an effective rainfall event is defined as an hourly rainfall depth greater than 4 mm, marking the beginning of a rainfall event. And when hourly rainfall depth is less than 4 mm for 6 consecutive hours, it is the end of that rainfall event. The estimating method of rainfall is practiced for issuing debris-flow and landslide warnings in Taiwan, and is extensively adopted by Lee (2006), and Chang et al. (2011).

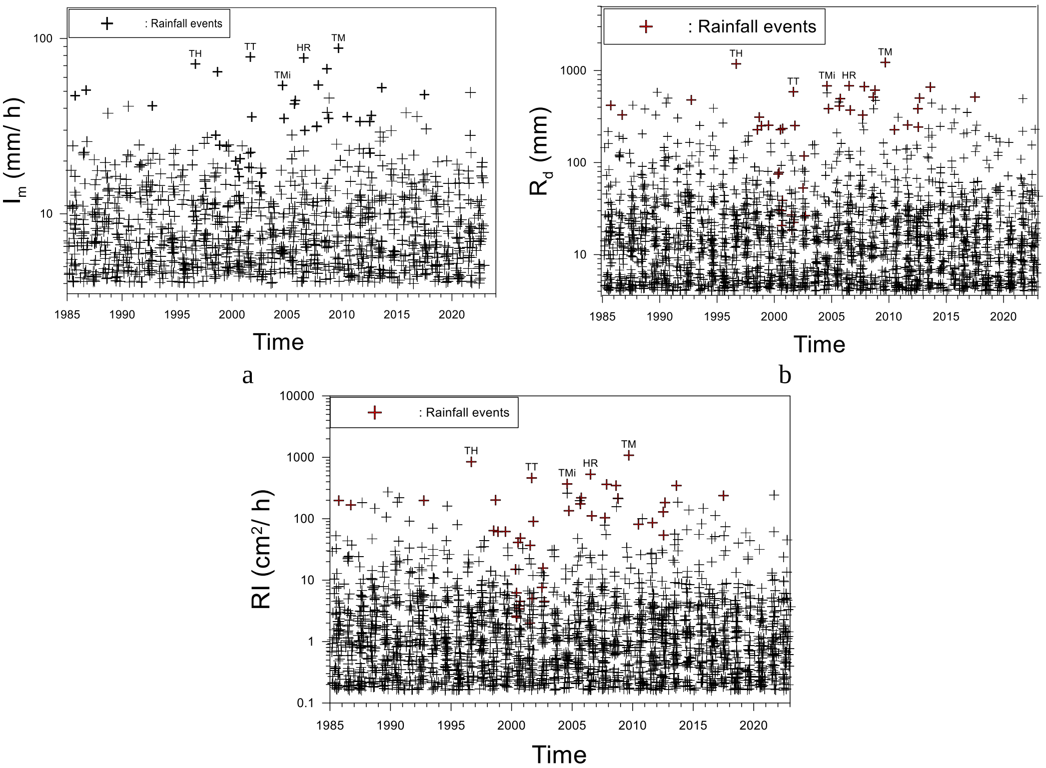
To investigate the variation in rainfall characteristics in the Chenyulan watershed, rainfall data from three meteorological stations – Sun Moon Lake, Yushan, and Alisan – located nearby or within the Chenyulan watershed, as shown in Fig. 1, were collected from the long-term records spanning 1985–2022. The three meteorological stations were used to estimate the regional average rainfall in the Chenyulan watershed employing the reciprocal-distance-squared method [*Chow et al., 1988*]. The estimated point using this method was located at the centroid of the watershed area, and it was used to determine rainfall characteristics, such as hourly rainfall, cumulative rainfall, rainfall duration, etc. [*Chen et al., 2012*].

Extreme rainfall may result in high hourly rainfall, high cumulative rainfall, or both. Debris flows caused by a rainfall event in the Chenyulan watershed generally occur within the period of maximum 24-h rainfall $R_d$ [*Chen et al., 2012*]; the maximum hourly rainfall $I_m$ is closely related to the occurrence of debris flows [*Chen et al., 2011*]. Moreover, $I_m$ and $R_d$ are rainfall indexes generally used to determine the rainfall conditions for debris-flow occurrence in an extreme rainfall event [*Cheng et al., 2005*]. Therefore, $I_m$ and $R_d$, determined from regional average rainfall for hourly rainfall in the Chenyulan watershed for each rainfall event, were collected, calculated, and analyzed in Fig. 2. To respond rainfall events by both high hourly rainfall and high cumulative rainfall, an extreme rainfall index $RI$ defined as $RI = R_d I_m$, was also calculated in Fig. 2. It shows the date and rainfall event, as well as the rainfall characteristics of each rainfall event in the watershed, including the maximum hourly rainfall $I_m$, the maximum 24-h rainfall $R_d$, and the extreme rainfall index $RI$. The five rainfall events, Typhoon Herb (TH) in 1996, Typhoon Toraji (TT) in 2001, Typhoon Mindulle (TMi) in 2004, Heavy rainstorm (HR) in 2006, and Typhoon Morakot (TM) in 2009, induced numerous debris flows with number$N \geq 10$ have $R_d$> 580 mm or $I_m$> 54 mm/h. Maximum $R_d$ and maximum $I_m$ in historical rainfall events (1963–2009), reaching as high as 1193 mm and 86 mm/h, respectively, were both caused by Typhoon Morakot in 2009.

## Debris-flows and landslides in the study area

Thirty-seven rainfall events, including 18 rainstorms and 19 typhoon-induced heavy rainfall events, have caused debris flows in the Chenyulan stream watershed [*Chen et al., 2012*], as shown in Fig. 3. Notably among these, heavy rainfall events were associated with Typhoon Herb in 1996, Typhoon Toraji in 2001, and Typhoon Morakot in 2009. Over the period from July 31 to August 1, 1996, Typhoon Herb hit Taiwan, bringing unexpectedly high cumulative rainfall (up to 1,994 mm within 2 days at the Alishan rainfall station near the headwater of the Chenyulan watershed), leading to 27 people dead and 14 missing [*Jan and Chen, 2005*]. The Chi-Chi earthquake of September 21, 1999 (moment magnitude 7.6) was the largest in Taiwan for hundred years [*Shin and Teng, 2001*]. The combination of the Chi-Chi earthquake in 1999 and extremely heavy rain associated with Typhoon Toraji in 2001 caused numerous large debris flows. In 2001, numerous debris flows occurred in central Taiwan, resulting in over 100 people dead or missing, and great damage to houses, roads, bridges, and dikes. In August 2009, Typhoon Morakot brought heavy rainfall, with maximum hourly rainfall of 123 mm and maximum cumulative rainfall of 2361 mm in 48 h recorded at the Alishan rainfall station. The typhoon damaged several river embankments, buried houses, caused bridge failures, and damaged numerous sections along Highway Route 21. In Shenmu and Tongfu villages, Xinyi

Township, over 20 houses were buried by debris flows or washed away by floods [*Chen et al., 2011*].



a

b

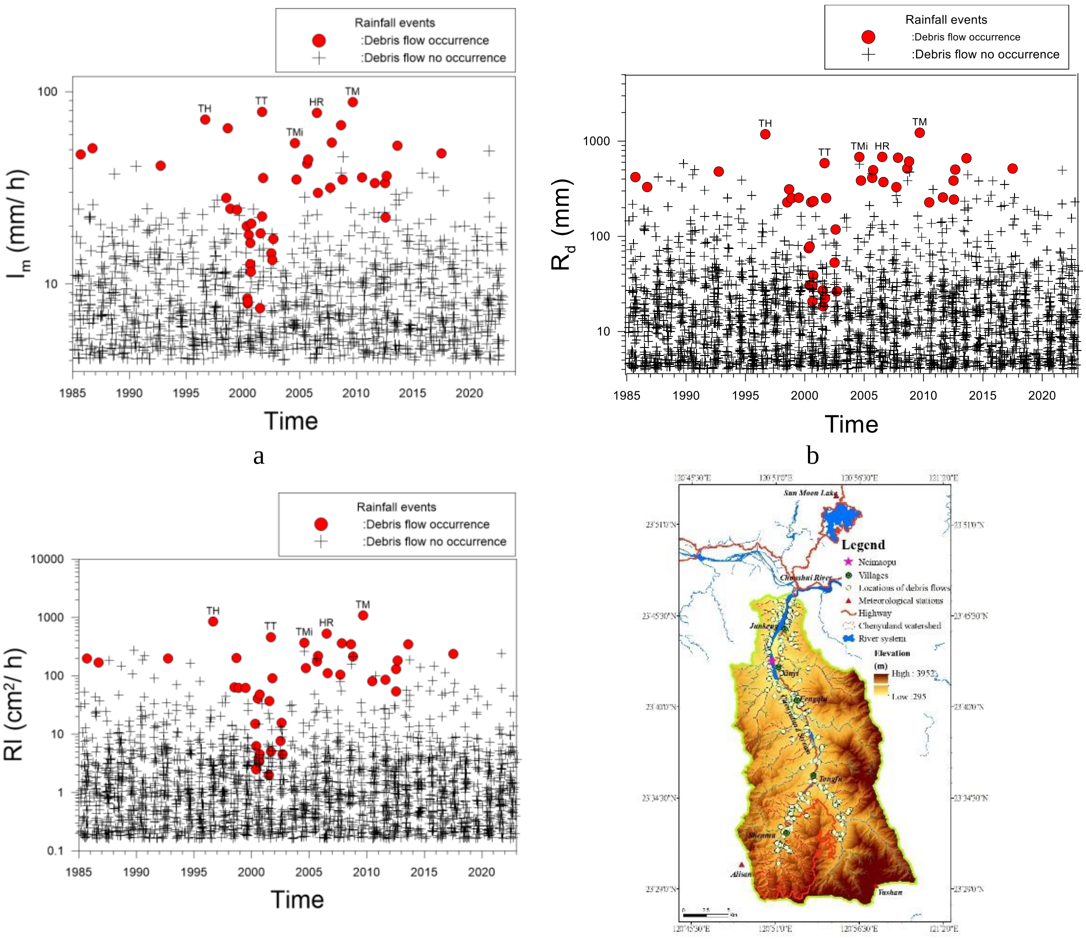
c

Fig. 2. Variability in the rainfall index $I_m$ between 1985 and 2022 (a). Variability in the rainfall index $R_d$ between 1985 and 2022 (b). Variability in the rainfall index *RI* between 1985 and 2022 (c)

The number of debris-flow events $N$ for each rainfall event and the locations of debris-flow events in the entire Chenyulan watershed from 1985 to 2022 were indicated in Fig. 3. Prior to 1996, the number of debris flows was determined from papers at local spots without covering the whole watershed because of lacking data from field investigations. After 1996, the number of debris flows $N$ used in this work was identified through interpretation of maps and field investigations. Fig. 3 showed that the five rainfall events, Typhoon Herb (TH) in 1996, Typhoon Toraji (TT) in 2001, Typhoon Mindulle (TMi) in 2004, Heavy rainstorm (HR) in 2006, and Typhoon Morakot (TM) in 2009, induced numerous debris flows with number $N \geq 10$. The maximum $N$ is 78 resulted by TT. The more severe debris flow events were caused by TH, TT and TM with number $N > 30$.

In the Chenyulan watershed, the hazardous earthquakes and rainstorms are main factors to trigger the landslides. Many researchers [*Lin et al., 2003; Cheng et al., 2005; Lin et al., 2006; Chiou et al., 2007; Lin et al., 2008; Chen, 2008; Chuang et al., 2009; Shou et al., 2011; Chang et al., 2011*] have studied the variation in the landslide areas before and after the Chi-Chi earthquake as well as the variation in the landslide areas caused by the consequent rainfall events after the earthquake. Among these studies, the analyzed results presented by Lin et al. (2003) and Chen (2008) are adopted in this study. To compare the studies offered by Lin et al. (2003) and Chen (2008), five SPOT images, six FORMOSAT-II images, and two PLEIADES 1A 7 images are adopted to analyze the earthquake-induced landslides and rainfall-induced landslides that took place before and after the Chi-Chi earthquake between 1988 and 2014. The images taken after typhoons with accumulated rainfall ranging from 229 mm to 2,472mm were analyzed. Besides, this study collects the landslides analysis results published by the SWCB, and presents the landslides analysis of the Chenyulan watershed from 2014 to 2016.

Before Typhoon Herb, the landslides areas only reached to 563.0 ha [*Yang et al.*, *2009*], which is regarded as the primary areas of landslide before the Typhoon Herb in the Chenyoulan watershed. Identification and calculation of landslide areas from the images are shown in Fig. 4. There is an obvious increasing trend in the landslide areas from 1988 to 2009. Before the 1999 Chi-Chi earthquake, the landslide areas have a slight increasing trend, the landslide areas increased slightly from 563.0 ha to 713.4 ha after the Typhoon Herb, and it is reasonably considered that rainfall events triggered these landslide areas. The landslide areas have been sharply amplified after the Chi-Chi earthquake, the landslide areas were greatly amplified and reached to 2084.1 ha, which is nearly tripled to 713.4 ha caused by Typhoon Herb. That is, after the 1999 Chi-Chi earthquake, there is a great increasing trend in the landslides area. Lin et al. (2006) indicated that the Chi-Chi earthquake not only triggered serious coseismic landslides itself but also extensively disturbed surface strata around the epicentral area, which may cause numerous landslides during the consequent rainfall events. Due to there was no significantly high precipitation after the Chi-Chi earthquake, the abrupt increase in landslide areas was most likely attributed to the Chi-Chi earthquake. Image measurement showed that the landslide area further expanded to 2749.7 ha in August 2001 after Typhoon Toraji, 2622 ha in July 2004, 1212 ha in June 2005, 950.59 ha in June 2008, and 1964.8 ha in June 2010, respectively. After 2009 Typhoon Morakot, the landslides area showed a noticeable decreasing trend, reducing to 1312.95 ha by September 2016 due to the diminishing effect of earthquakes and the significant investment by the SWCB in building the conservation works in the Chenyoulan watershed.



a b

c d

Fig. 3. Variability in the rainfall index $I_m$ related to debris-flow occurrences between 1985 and 2022 (a). Variability in the rainfall index $R_d$ related to debris-flow occurrences between 1985 and 2022 (b). Variability in the rainfall index *RI* related to debris-flow occurrences between 1985 and 2022 (c). Locations of debris flows in Chenyulan stream watershed between 1985 and 2022 (d)

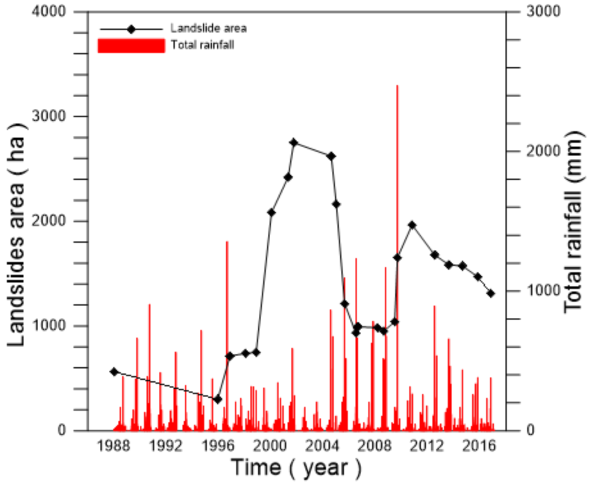


Fig. 4. Variability in the rainfalls related to different periods landslides in Chenyulan stream watershed between 1986 and 2016

## Conservation structures in the study area

Kauki et al. (1988) indicated the sediment control and deposit effect of Sabo dam, conservation works, are obviously, different configurations will produce different amounts of inhibition, including the outflow of sediment, suppression (sand storage corresponding to existing space and planned facilities) and the amount of regulation. In general, the planned riverbed slope can be set to half of the original riverbed slope, and the adjusted slope is set to 2/3–3/4 of the original riverbed slope. Lien and Tsai (2013) showed sediment control is quantifiable in soil and water conservation engineering. For example, Sabo Dam not only prevents stream bed erosion but also stores sediment. Sabo Dam can stabilize a foundation part of the slope and can stabilize the entire slope as well, as shown in Fig. 5. The method for calculating the stability of slope effect for soil and water conservation engineering is used to calculate the sediment control of the Sabo Dam and bank revetment under three kinds of soil and water conservation engineering. The structures of conservation can effectively control or reduce the outflow of sediment from the creeks.

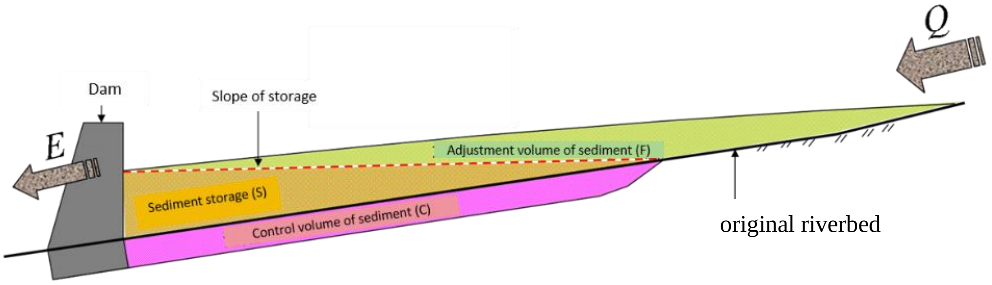


Fig. 5. The indication of sediment control of Sabo dam

The sediment control capabilities of Sabo Dam can be expressed as follows:

1. Sediment storage ($S$): To prevent the outflow of sediment from the riverbed upstream of the sand dam (or the original upstream of the dam). Based on the sediment of the riverbed, the amount of sediment storage and its volume can be calculated according to the equation:

$$V = \frac{1}{2}\frac{m\cdot n}{m-n}\cdot b\cdot h^2, \qquad (1)$$

where $V$ – the amount of sediment storage; m: target siltation slope reciprocal; $n$ – the reciprocal of the original riverbed slope; $b$ – average siltation width; $h$ – the height of dam.

2. Adjustment volume of sediment ($F$): The adjustment of target riverbed slope is based on the original river. The riverbed slope is set at 2/3, but when the riverbed slope is steep and there is a presence of large sand particles and gravel leading to substantial outflow, it can be assumed to be adjusted to 2/3 to 3/4 of the original riverbed slope.
3. Control volume of sediment ($C$): The sediment control basically refers to the amount of sedimentation that the riverbed can regenerate. Therefore, sedimentation deposited in upstream of the dam within the control range can achieve sedimentation production to prevent riverbed erosion. The length of silt ($L$) can be calculated according to equation:

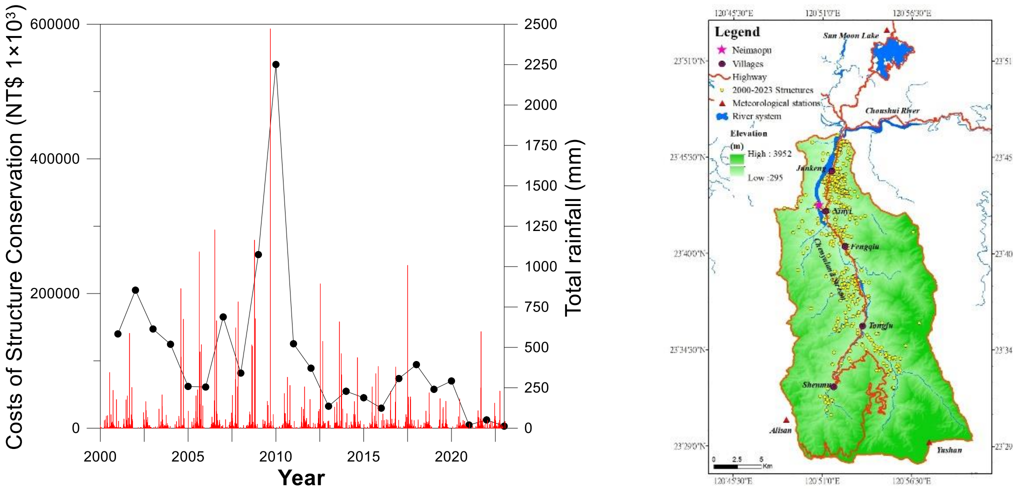
$$L = \frac{m \cdot n}{m - n} \cdot h. \tag{2}$$

Besides, Chen and Zhang (1996) referenced Japanese sedimentation control structures to define formula and calculate the prevention of sedimentation volume in various longitudinal and horizontal conservation structures in rivers. Therefore, conservation structures can indeed effectively control the soil and downward movement of sediment in riverbanks.

$$S_2 = 2h_2 \cdot L_2, \tag{3}$$

where $S_2$ – the amount of sediment control for revetment; $h_2$ – effective height of revetment; $L_2$ – the length of the revetment.

To further understand the effects of implementing conservation structures, the data on these structures, including engineering names, costs, locations, engineering contents, and landslide improvements, etc., was collected through the engineering system of SWCB between 2001 and 2022. Due to the large number of categories of conservation structures that are difficult to quantify directly, this study only analyzes the annual government investment funds. It combines rainfall events, which cause conservation needs, to provide variation in conservation projects over the last few decades. The variations of rainfall events and conservation funds are shown in Fig. 3. It shows that Typhoon Toraji in 2001 resulted in widespread landslides and numerous debris flows after the 1999 Chi-Chi earthquake. The government invested a significant amount of engineering funds, totaling NT 140,004,000, after Typhoon Toraji in 2001. After Typhoon Minduli in 2004, the government once again invested funds, totalng NT 124,617,000. Typhoon Morakot In 2009 brought high-intensity rainfall and record-breaking cumulative rainfall, resulting in the most severe landslides and debris-flow disasters on record in the Chenyulan stream watershed. As a respond, the government invested a record-high amount of funds in engineering conservation, with a total budget of NT 540,183,000. Due to continuous investment in conservation projects and governance engineering funds, coupled with a relatively gradual decrease in high-intensity rainfall in recent years, government engineering funds have been decreasing year by year. Since 2010, SWCB engineering funds have shown a decreasing trend. Additionally, after engineering conservation of landslide and debris flow in the last decades, the amount of suspended sediment discharges in river channels has significantly slowed down. This gradual improvement has led to sediment levels gradually approaching the standards observed before Typhoon Toraji. This indicates that the investment in conservation projects in recent years has had significant engineering benefits, resulting in a decrease in soil disasters such as landslides and debris flows. Moreover, changes in the suspended sediment discharges at the Neimaopu hydrology gauging station downstream of the Chenyulan stream watershed reflect this positive trend. These findings will be further elaborated in the next section.



a b

Fig. 6. Variability in the rainfall depth related to costs of conservation constructions between 2001 and 2022 (a). Locations of conservation constructions in the Chenyulan stream watershed between 2001 and 2022 (b)

## Suspended sediment discharges in the study area

The data of suspended sediment discharges are also collected based on the Neimaopu hydrology gauging station during the period from 1972 to 2019. The Rating Curve Method [*Walling, 1977; Crawford, 1991; Lin, 2005; Lin et al, 2008*] is adopted to estimate sediment discharges during the rainy events. The Rating Curve Method is useful when an empirically calibrated power-law relationship between the flow discharge and the sediment concentration can be defined. The empirical formula is as follows:

$$Q_s = aQ^b, \tag{4}$$

where $Q_s$ is suspended sediment discharge (t/day) and $Q$ is daily average discharge (cm/s). The formula is evaluated by taking the logarithm of each coordinate axis. The parameters, $a$ and $b$, are determined by using least-square regression. By mean of established empirical formula, the $Q_s$ can be obtained by given discharge $Q$. The relationship between the daily average discharge $Q$ and the suspended sediment discharge $Q_s$ is established. Likewise, the collected hydrometric data is divided into six parts to understand the variations in suspended sediment discharges in the Chenyoulan stream over recent decades (Fig. 7).

Fig. 7 presents the relationship between the daily average discharge $Q$ and the suspended sediment discharge $Q_s$ between 1972 and 2019. It is observed that the higher daily average discharge $Q$ corresponds to a suspended sediment discharge $Q_s$ is different from the lower $Q$ corresponding to $Q_s$ in Fig. 7. Additionally, the correspondence between $Q$ and $Q_s$ varies for each decade. Therefore, the observed data in this study is not only divided into six periods, namely 1970–1979, 1980–1989, 1990–1999, 2000–2004, 2000–2009, and 2010–2019 respectively, but also into two conditions, $Q > 50$ cm/s and $Q < 50$ cm/s. This division allows for a deeper understanding of the variations in $Q_s$ under different conditions of $Q$, as shown in Fig. 7.

In Fig. 7, the bold black line represents the regression line obtained by the data of $Q$ and $Q_s$ between 1972 and 2019 under conditions where $Q < 50$ cm/s. The power regression formula describes the line in the form of $Q_s = 0.19Q^{2.70}$. The holly triangles represent the data between 1972 and 1979 and the bold orange line represents their regression line obtained by data of $Q$ and $Q_s$; the power regression formula describes the line in the form of $Q_s = 0.10Q^{2.70}$. The bold green line represents the data obtained between 1980 and 1989; the power regression formula is in the form of $Q_s = 0.16Q^{2.70}$. The bold blue line represents the data obtained between 1990 and 1999; the power regression formula describing the line takes the form as $Q_s = 0.40Q^{2.70}$. The bold red line represents the data obtained between 2000 and 2009; the power regression formula describing the line is in the form of $Q_s = 0.60\mathrm{Q}^{2.70}$. The bold light blue line represents the data obtained between 2010 and 2019; the power regression formula describing the line is in the form of $Q_s = 0.58Q^{2.70}$. Besides, the relationship between $Q$ and $Q_s$ during the period affected by the Chi-Chi earthquake (2000–2004) is discussed separately. The dotted black line represents the data obtained between 2000 and 2004; the power regression formula describing the line is in the form of $Q_s = 1.10Q^{2.70}$.

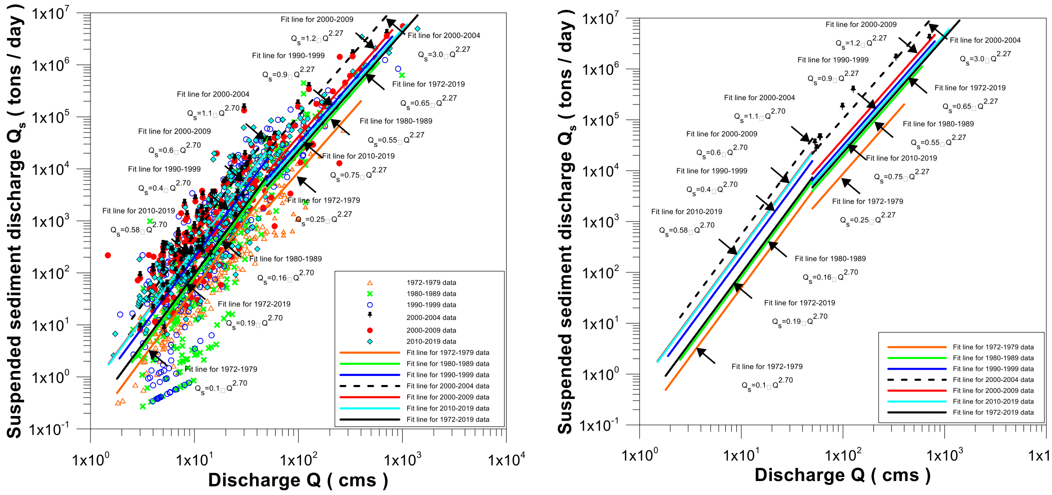
Fig. 7, the suspended sediment discharge obtained in 1972–1979 and 1980–1989 is 1 to 2 times smaller than that in 1972–2019 when $Q < 50$ cm/s; while that obtained in 1972–1979 and 1980–1989 is 1 to 3 times smaller than that in 1972–2019 when $Q > 50$ cm/s. The suspended sediment discharge acquired in 1990–1999 is 2 to 3 times more than that in 1972–2019 when $Q < 50$ cm/s; while that acquired in 1990–1999 is 1 to 2 times more than that in 1972–2019 when $Q > 50$ cm/s. The suspended sediment discharge gained in 2000–2009 is 3 to 4 times more than that in 1972–2019 when $Q < 50$ cm/s; while that gained in 2000–2009 is 1 to 2 times more than that in 1972–2019 when $Q > 50$ cm/s. The suspended sediment discharge gained in 2000–2004 is 5 to 6 times more than that in 1972–2019 when $Q < 50$ cm/s; while that gained in 2000–2004 is 4 to 5 times more than that in 1972–2019 when $Q > 50$ cm/s. The reason why the suspended sediment discharges in 1990–1999 and 2000–2009 are greater than those in 1972–1979 and 1980–1989 can be reasonably attributed to the variability in rainfall during those decades. The cause that the suspended sediment discharge in 2000–2009 is greater than that in 1972–1979, 1980–1989, 1990–1999 and 2010–2019 can be ascribed not only to the rainfall variability during this decade but also to the effects of the Chi-Chi earthquake.

The earthquake caused numerous landslides and increased the number of crakes on the hill slopes of creeks. After the Chi-Chi earthquake, a large number of debris rocks were deposited, providing the conditions necessary for triggering debris flows and enhancing the rate of soil erosion in the entire watershed during subsequent rainy events. In Fig. 8, the suspended sediment discharge obtained during 2000–2009 is significantly larger than that in the other periods, both when $Q < 50$ cm/s and when $Q > 50$ cm/s. The small discharges can deliver high suspended sediment discharges which attribute to the loose debris materials caused by the Chi-Chi earthquake. Due to the variation in sediment yields have violently changed in each creek, the variations in the suspended sediment discharges are analyzed before and after the Chi-Chi earthquake.

In addition, since the 2001 Typhoon Toraji, the SWCB has continued to invest in conservation funds, especially after the 2009 Typhoon Morakot. A significant number of conservation projects were constructed, and creeks were reorganized, resulting in a gradual decrease in the suspended sediment discharge of the river year by year. The suspended sediment discharge between 2010 and 2019 has been close to the suspended sediment discharge observed before Typhoon Toraji in 2001. This indicates that the conservation projects invested by the SWCB have likely achieved the expected results.

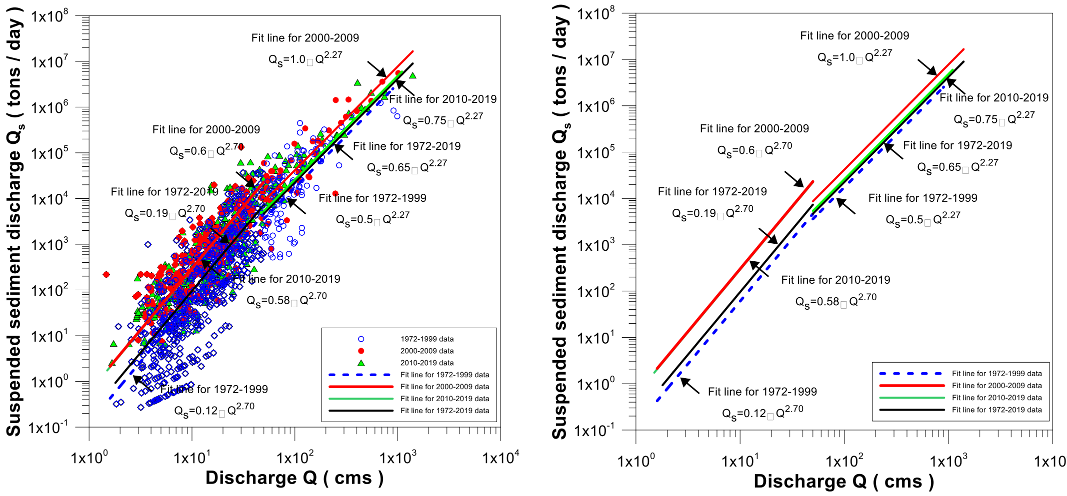
Table 1. Empirical coefficients of *a* and *b* for the six studied periods

| Period (when $Q < 50$ cms) | *a* | *b* | Period (when $Q > 50$ cms) | *a* | *b* |
|---|---|---|---|---|---|
| 1972–1979 | 0.10 | 2.70 | 1972–1979 | 0.25 | 2.27 |
| II. 1980–1989 | 0.16 | 2.70 | II. 1980–1989 | 0.55 | 2.27 |
| 1990–1999 | 0.40 | 2.70 | 1990–1999 | 0.90 | 2.27 |
| IV. 2000–2004 | 1.10 | 2.70 | IV. 2000–2004 | 3.00 | 2.27 |
| V. 2000–2009 | 0.60 | 2.7 | V. 2000–2009 | 1.2 | 2.27 |
| VI.2010–2019 | 0.58 | 2.7 | VI.2010–2019 | 0.75 | 2.27 |
| VII.1972–2019 | 0.19 | 2.7 | VII.1972–2019 | 0.65 | 2.27 |



a b

Fig. 7. Variations of $Q$ and $Q_s$ during different decades at the Neimaopu hydrology gauging station (1972–2019) (a). Variations of the rating curves estimated by $Q$ and $Q_s$ during different decades at the Neimaopu hydrology gauging station (1972–2019) (b)



a b

Fig. 8. Variations of $Q$ and $Q_s$ before and after Chi-Chi earthquake at the Neimaopu hydrology gauging station (1972–2019) (a). Variations of the rating curves estimated by $Q$ and $Q_s$ before and after Chi-Chi earthquake at the Neimaopu hydrology gauging station (1972–2019) (b)

## Conclusions

The conservation investment funds for debris-flow and landslide disasters in the past decade have shown a tendency to slow down. Due to the reduction in disasters, the SWCB had no funds to invest in 2022, indicating that the situation of slopes in the Chenyulan Watershed has stabilized and the impact of the Chi-Chi earthquake has been alleviated.

The engineering conservation measures have been implemented to trap the loose soil on slopes of creeks, such as the control and deposit effect of dams. This includes the storage of outflow sediment, suppression and regulation of the amount, control of the loose sediment in the upstream. All these effectively reduce suspended sediment discharges.

SWCB continuous investment in engineering and funding since 2001 Typhoon Toraji has led to the establishment of the main conservation structures at the creeks with higher potential for debris flows and landslides in upstream. Therefore, there are currently no further conservation requirements.

The decrease in debris-flow events, landslides, and suspended sediment discharges demonstrates that the continuous conservation works have effectively controlled soil erosion on slopes through the implementation of structure conservation in the watershed over the last decade.

The suspended sediment discharges between 2010 and 2019 have returned to levels similar to those observed before Typhoon Toraji in 2001. This indicates that the conservation projects invested by the SWCB have likely achieved the expected results.

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