Sediment Discharge and Landslides in Mountain Area of Taiwan

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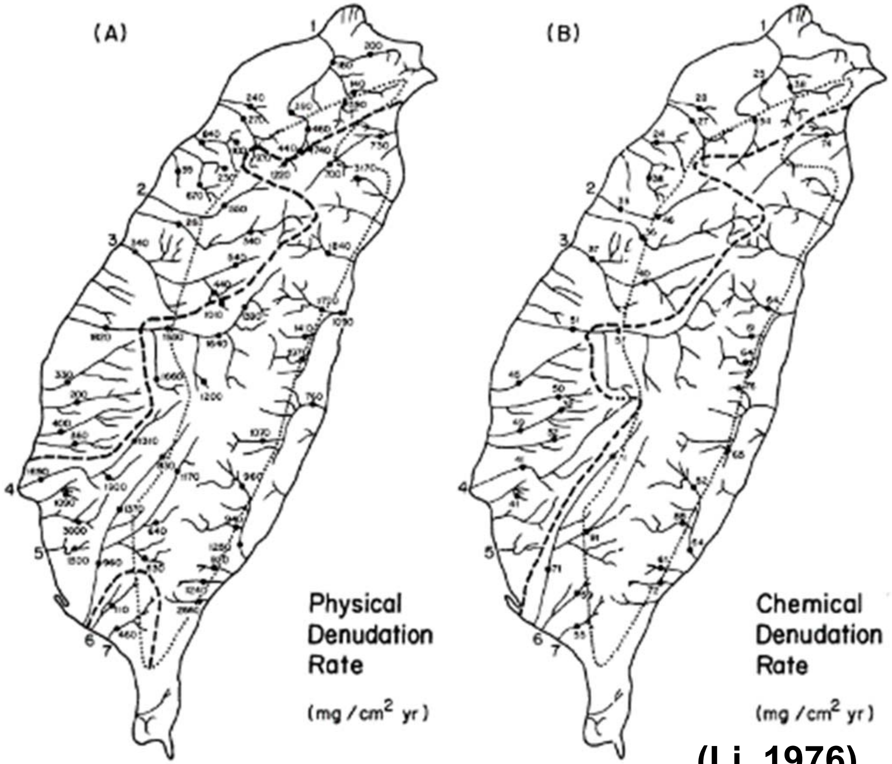
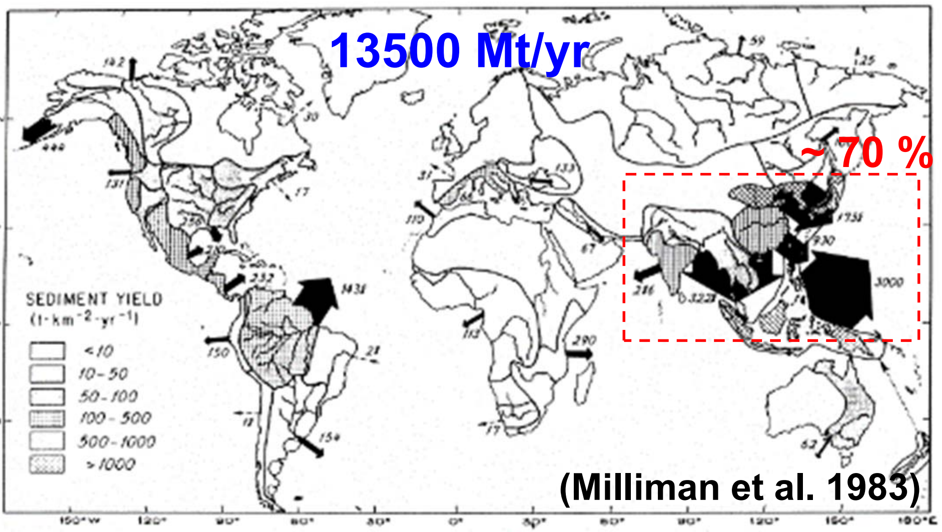
Outline

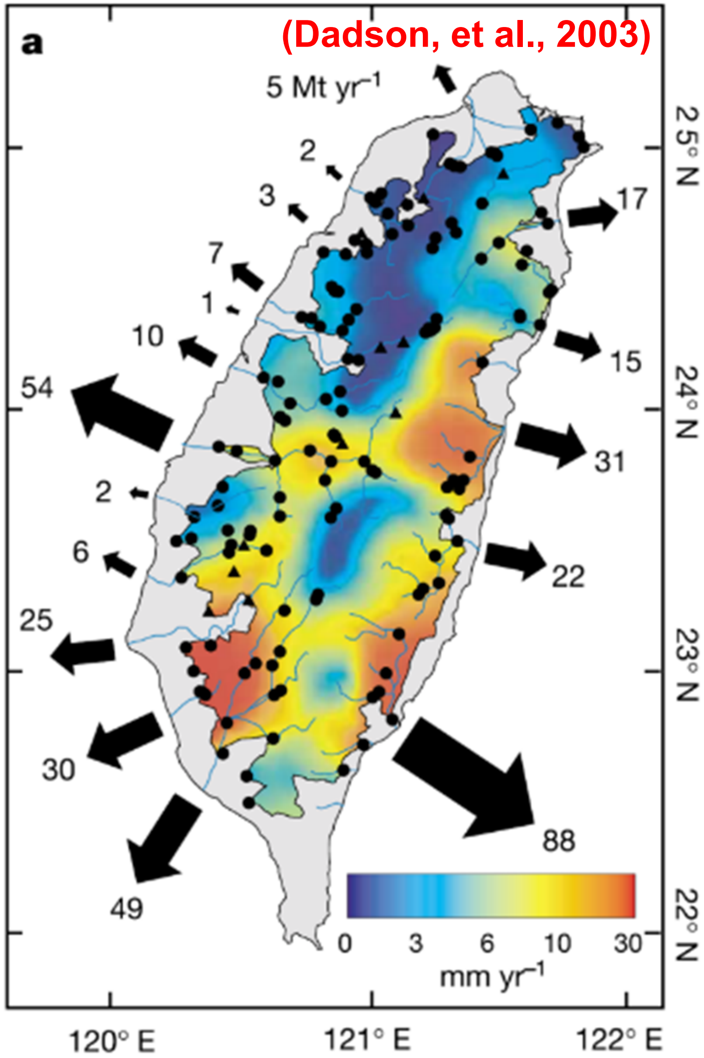
1. Background and motivation
2. Investigation and analysis methods
3. Results of tests and analysis
4. Influences on landslide and sediment discharge
5. Links between landslide location and rivers
6. Recovery period of sediment discharge
7. Conclusions

Background and motivation



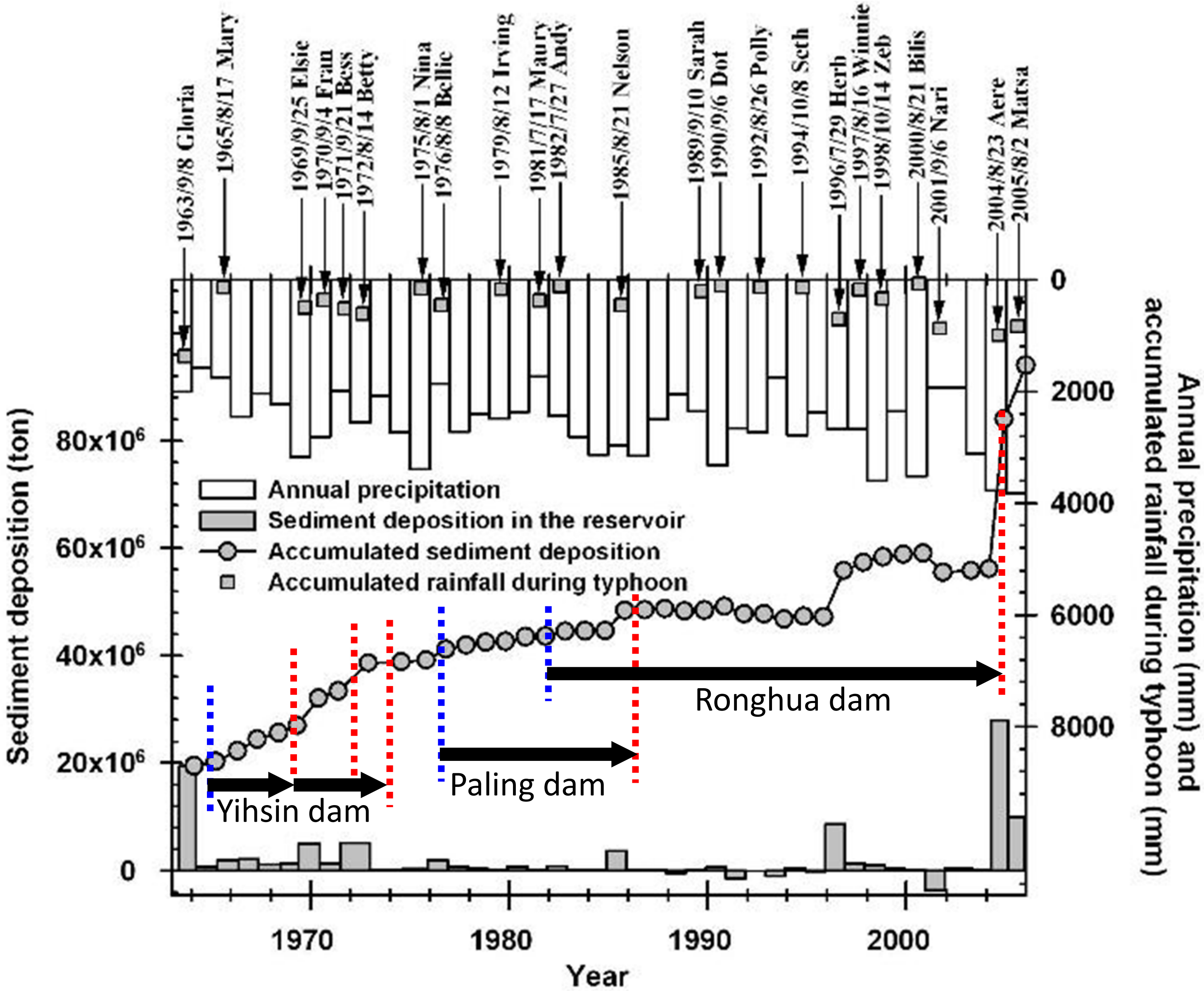
(Li, 1976)





Average annual sediment discharge (1970-1999) = 354 Mt/yr (2.6%)

Sediment deposit in reservoir



Sediment Problem: Quick accumulation rate in reservoir area


Tien-Lun Dam (Tachia River)
Quick accumulation rate during storm.
Huge amount of landslide debris was
delivered into reservoir area.
Before 1999
Need a lot of $ and time to recover.
A big typhoon can make a dam broken.
2004.08

Wan-Da Reservoir

During 2008/9/9 Sinlaku typhoon, huge amount of sediment was delivered to Wan-Da reservoir area. It is difficult to execute clear-up project.

Problem on reservoir operation
Shorten life duration of reservoir

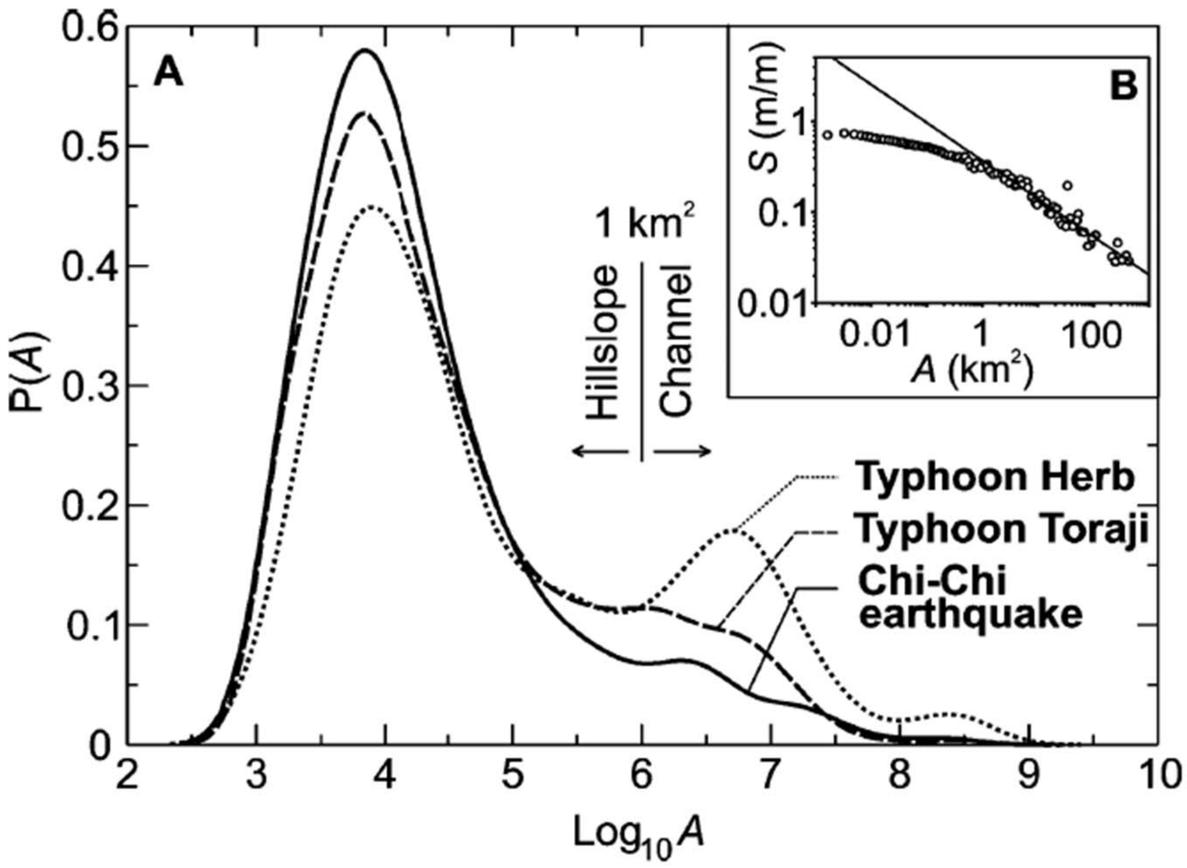
2010.11

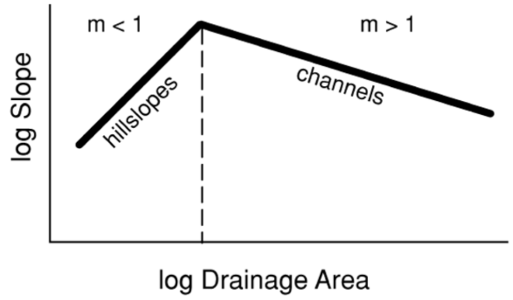
Consequent hazards would be expected in the following years.

Taimali River

Huge sediment was delivered to downstream area and change topography of river channel.

Where did landslides stay?





$$Qs = kA^m S^n = UA$$

$$S = \left(\frac{U}{k}\right)^{\frac{1}{n}} A^{\frac{1-m}{n}}$$

k: constant
A: drainage area
S: local slope
U: rock uplift rate

(Montgomery, 2001)

Most of landslides remained confined to hillslopes (Dadson et al., 2004**)**. Only *13%* of landslides triggered by Typhoon *Toraji*, and *24%* of landslides triggered by Typhoon *Herb*, delivered sediment to the channel network**.** Sediment problem was not solved immediately after events.

Objectives

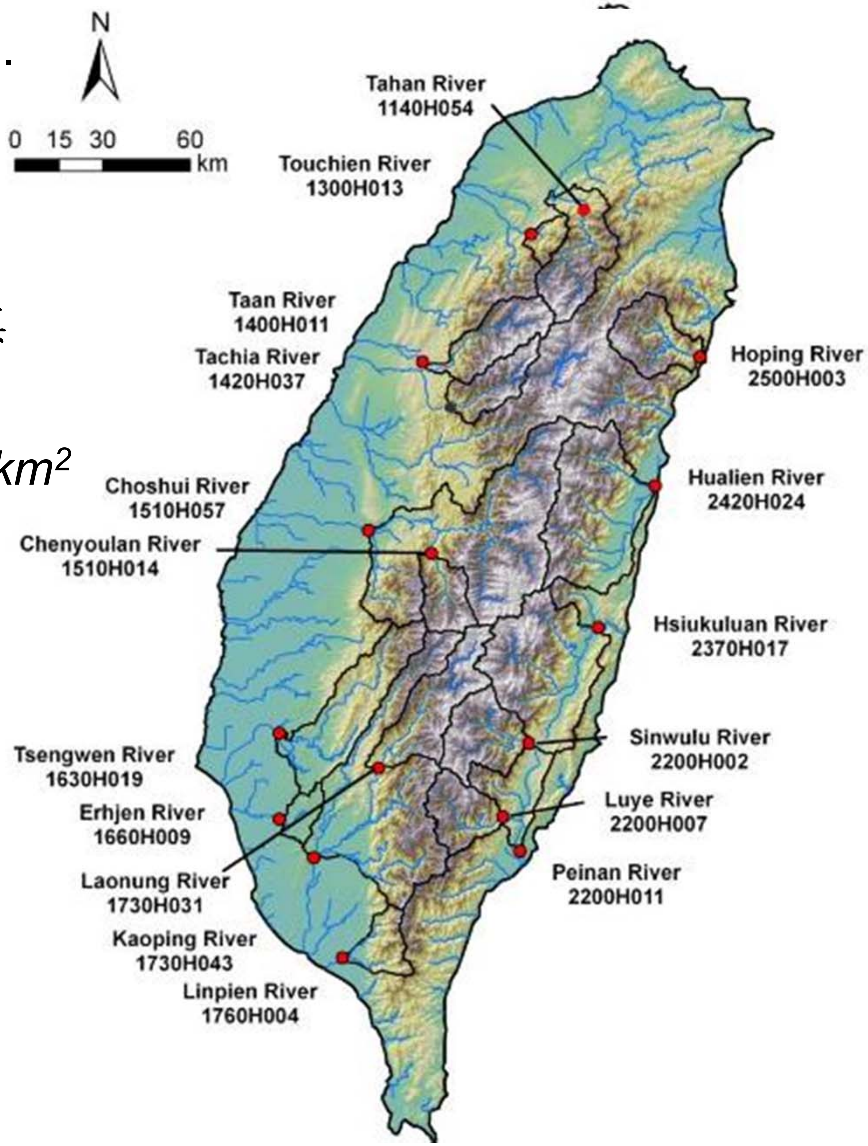
- Effects of inherent conditions (geomaterial properties, geomorphology, etc.) on landslide occurring and extreme hydraulic phenomenon.

- Impact of extreme events (rainstorm, earthquake)
  - Change of landslide characteristics
  - Variation of sediment supply rate

- Possible recovery period after extreme events

Study areas – Main catchments in Taiwan

- The study contains *13* main rivers in Taiwan.
  - North:大漢溪、頭前溪
  - Central:大安溪、大甲溪、濁水溪
  - South:曾文溪、二仁溪、高屏溪、林邊溪
  - East:和平溪、花蓮溪、秀姑巒溪、卑南溪
- Total area of 13 river catchments is *14,733* km^2 (~*62 %* of mountain region).
- The geology of study areas composed of *Western Foothills belts*, *Hsuehshan Range*, *slate belt*, *Tananao schist*, *coastal Range*.
- The ratio of sedimentary formations to metamorphic formations is *3:7*.



Study methods

(1) Investigations of rock properties

- Rock strength
- Joint density

(2) Hydrological analysis

- Suspended sediment discharge
- Turbidity-flow concentration (~40,000 ppm)

$$TSS = \frac{365}{n}\sum_{i=1}^{n}\left(\frac{86400}{1000000}\kappa Q_i^{b+1}\right) + \frac{1}{n}\sum_{i=1}^{n}\exp(\varepsilon_i)$$

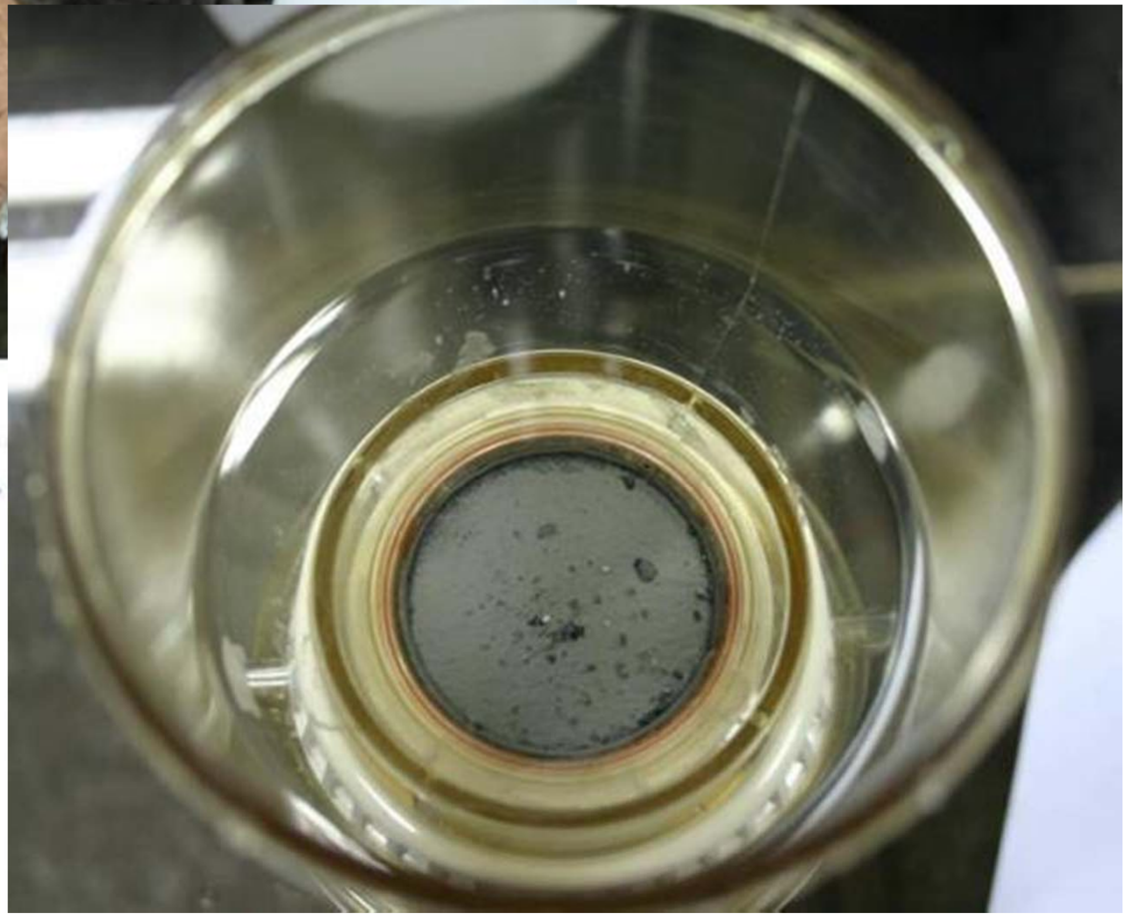
- *TSS*: total sediment discharge (t)
- m_i: times of observation of the ith month
- Q_i: flow discharge of the *i*th day (m^3/sec)
- κ: unit sediment concentration (ppm)
- *n*: times of observation
- *b*: coefficient of rating curve
- ε_i: log-regression residual

(3) Landslide analysis on GIS

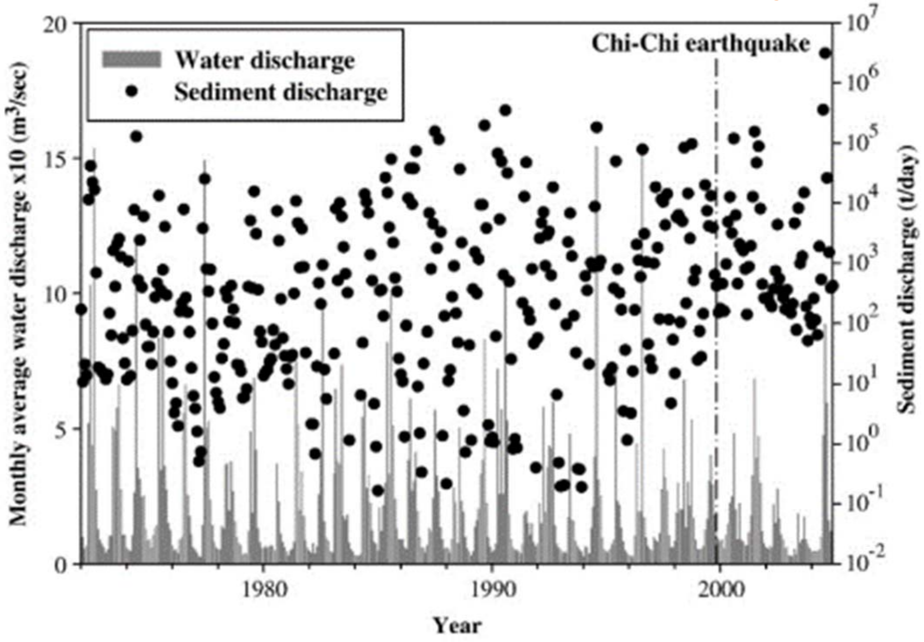
- Landslide ratio, new-generation/reactivated ratio
- Landslide location

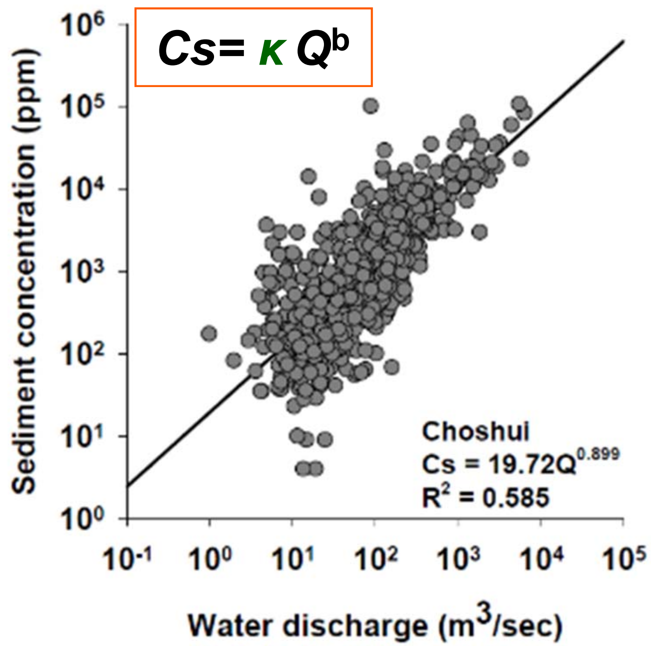


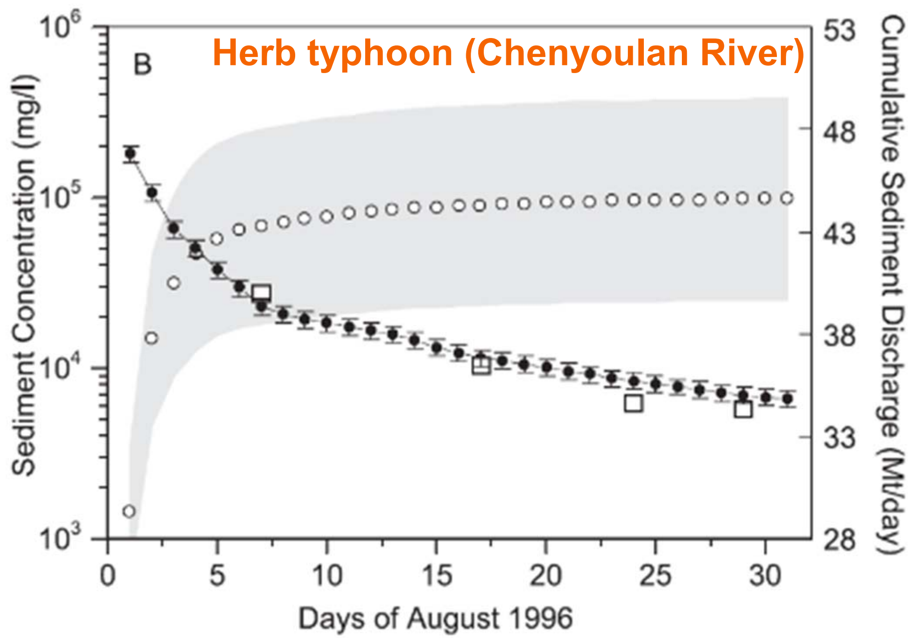
Material of hydrometric analysis



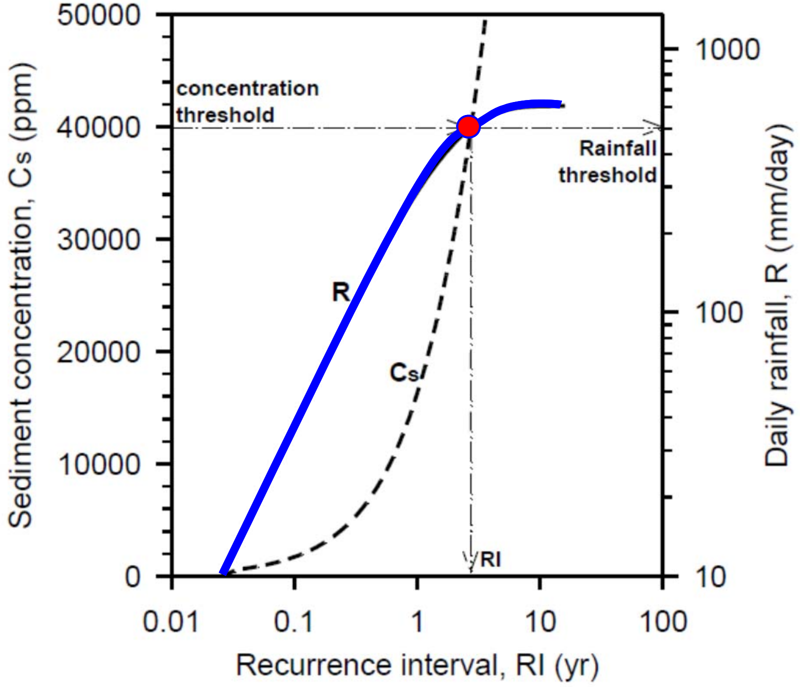
Material of hydrological analysis





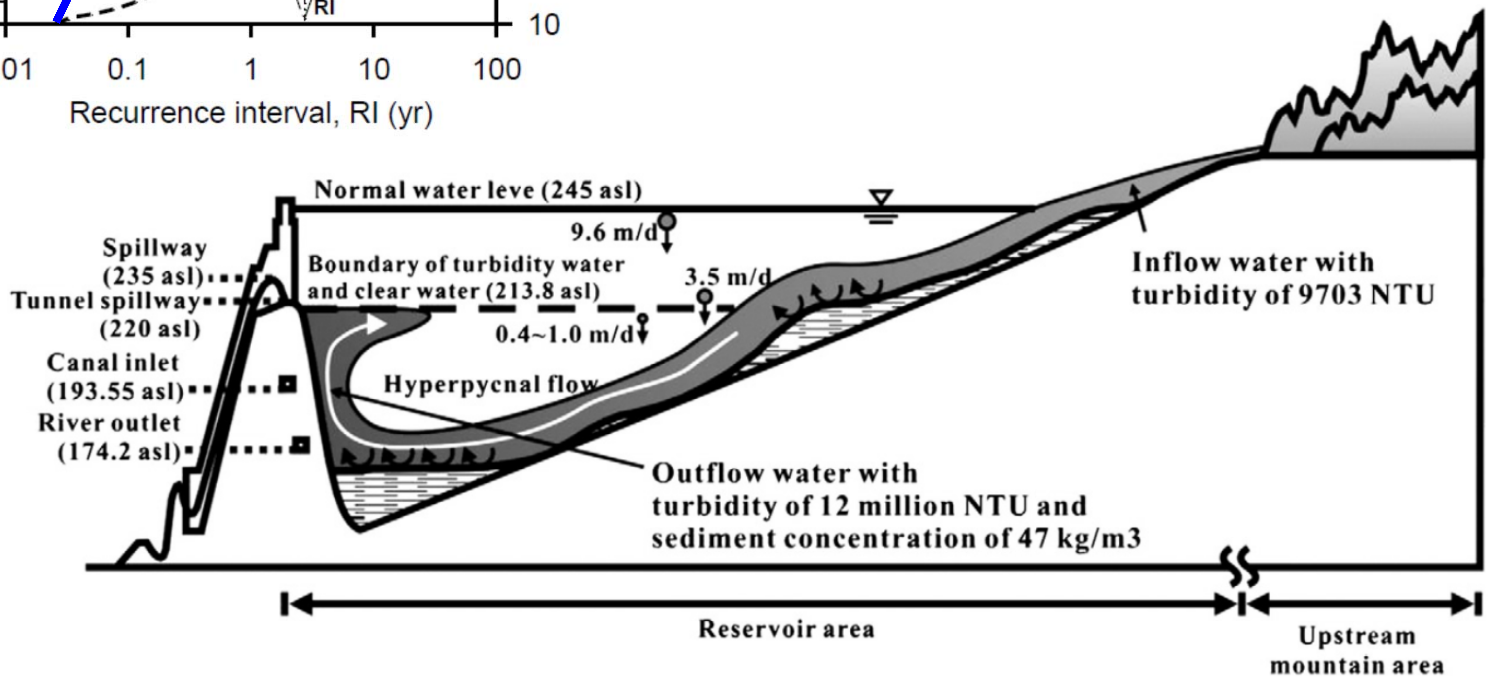


Turbidity-flow Concentration & Rainfall Threshold



Whenever high-concentration water flows into a reservoir area, lake or ocean, the density differences between the two water bodies will induce the high-concentration water to sink to the bottom, below the low-concentration water, and turbidity flow forms.

$$\text{Recurrence Interval, } RI = \frac{(T+1)}{N_i}$$



Rainfall

-Hurly rainfall

-24hrs rainfall

-Cumulative rainfall

Sediment discharge

-Hurly sediment discharge

-Cumulative sediment discharge

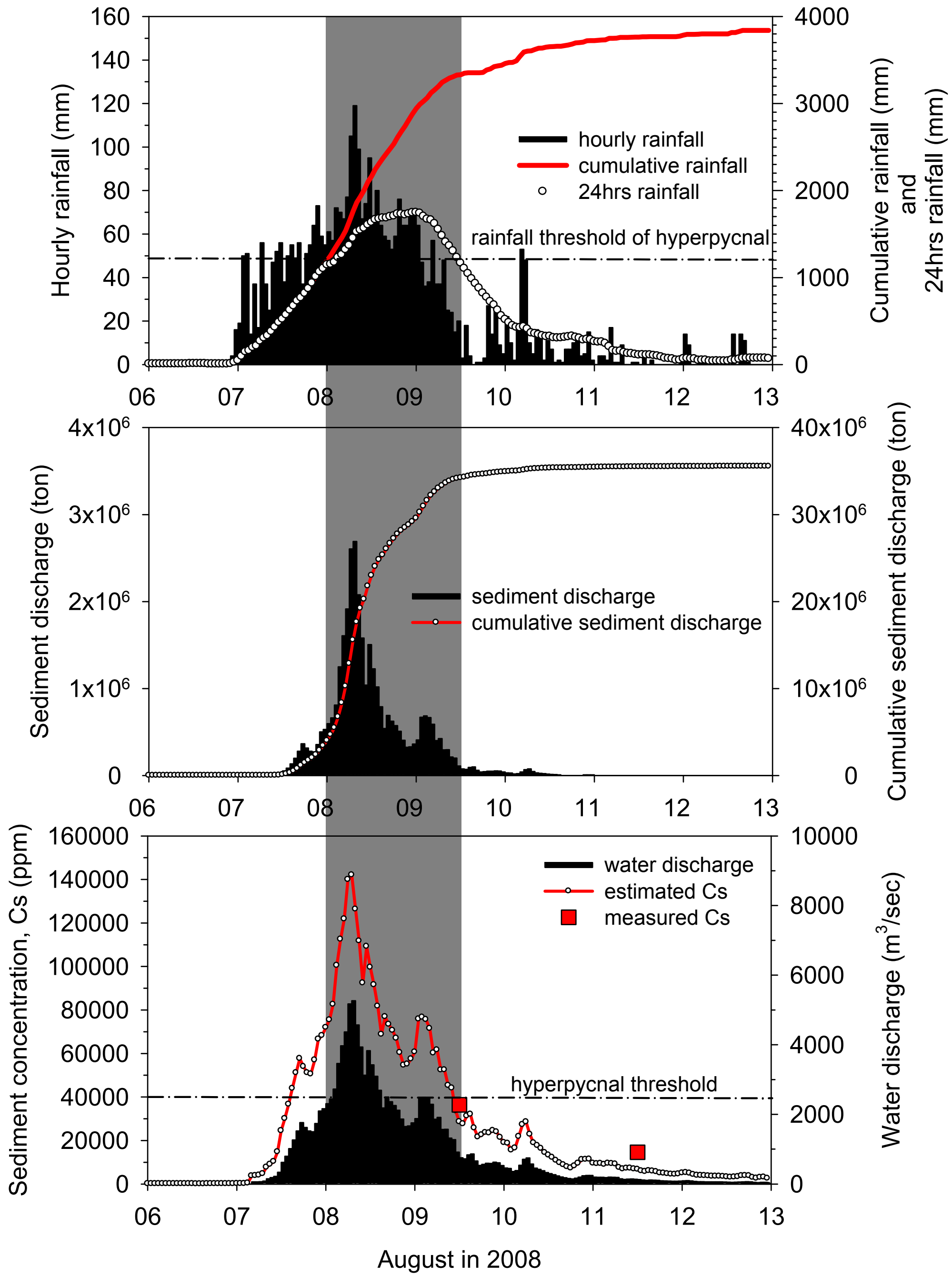
$$Cs = \kappa Q^b$$

Water discharge/sediment concentration

-Hurly water discharge

-Measured sediment concentration

-Estimated sediment concentration



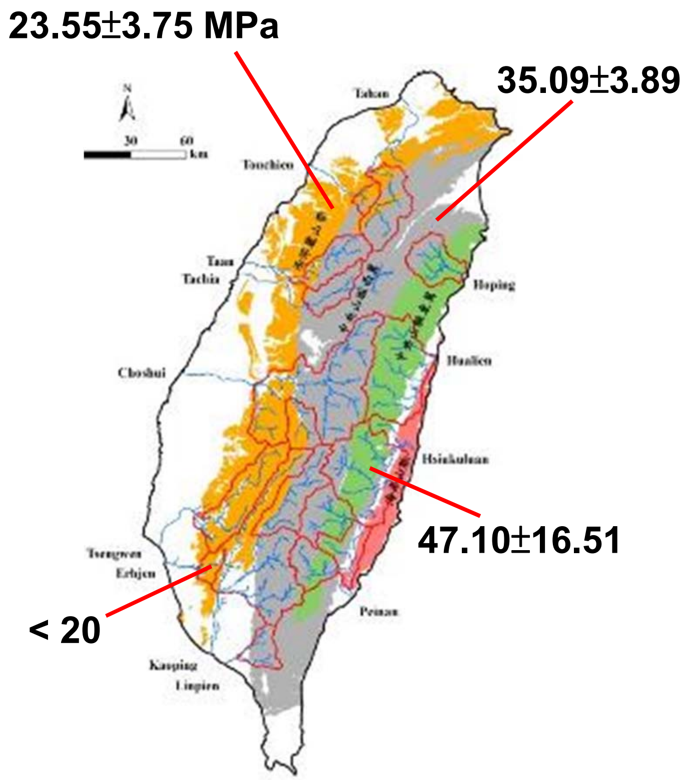
Results of tests and analysis

(1) Rock strength and joint density in the study catchments

$$J_V = \frac{N_1}{L_1} + \frac{N_2}{L_2} + \frac{N_3}{L_3} + \dots + \frac{N_n}{L_n}$$

N_i: joint number of the ith set of discontinuity
L_i: investigated length of the ith set of discontinuity

Catchments	Rock strength UCS (MPa)	Joint density Jv (m^{-3})	Test sets
Tahan River	***56.32***	**19.22**	**75**
Touchien River	**39.18**	**7.58**	**71**
Taan River	**28.03**	**7.81**	**23**
Tachia River	**45.00**	**11.34**	**47**
Choshui River	**31.02**	**22.93**	**128**
Tsengwen River	***17.77***	**6.83**	**49**
Erhjen River	***11.40***	***1.73***	**42**
Kaoping River	**27.49**	**20.20**	**121**
Linpien River	**25.91**	***53.08***	**23**
Hoping River	**30.17**	**21.09**	**18**
Hualien River	**33.45**	**22.66**	**31**
Hsiukuluan River	**30.59**	**38.35**	**26**
Peinan River	**41.84**	**24.52**	**70**



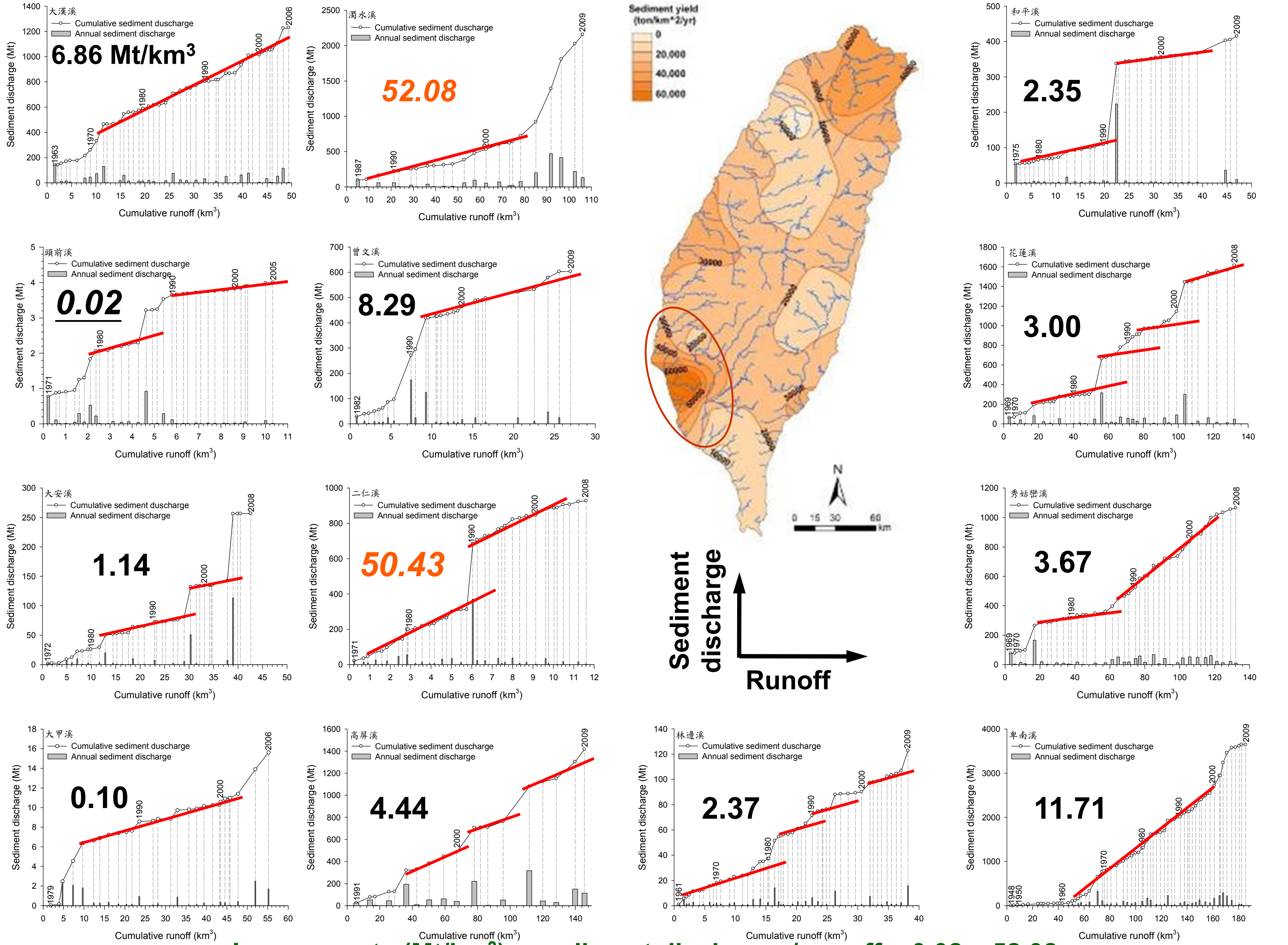
The outcrop of mudstone leads to lower average rock strength.
Rock strength in south region is lower than other region.
Rock strength increases from west region to east region.

Results of tests and analysis

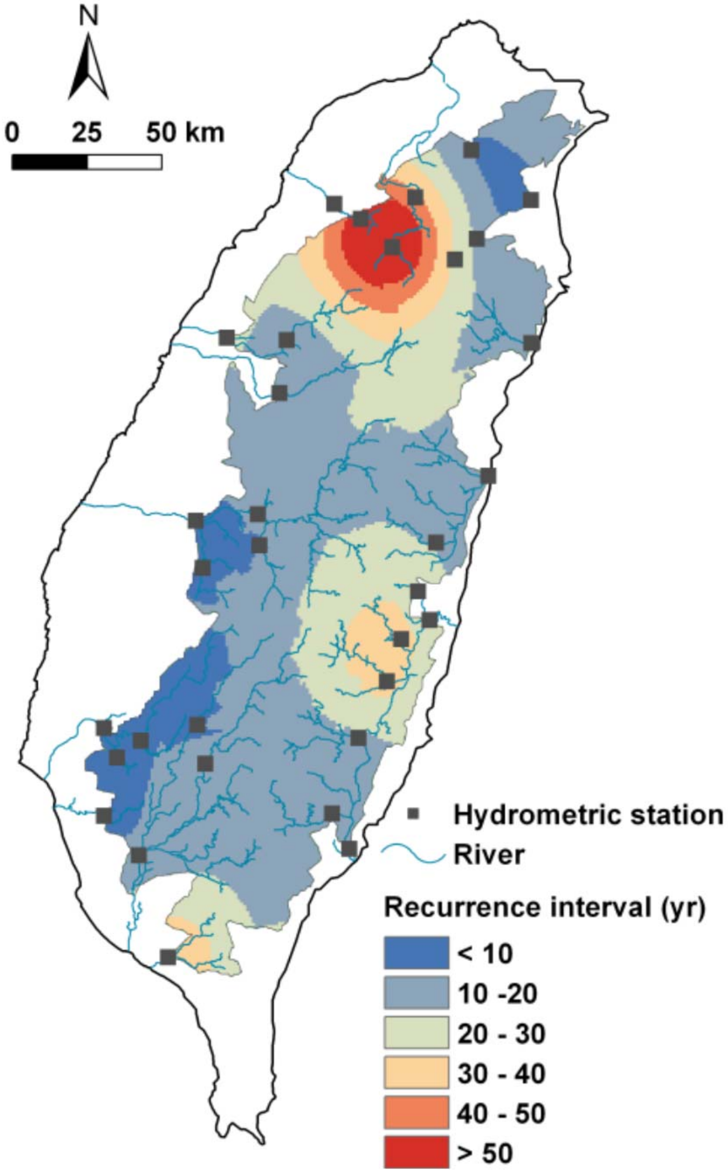
(2) Sediment discharge from mountain catchments

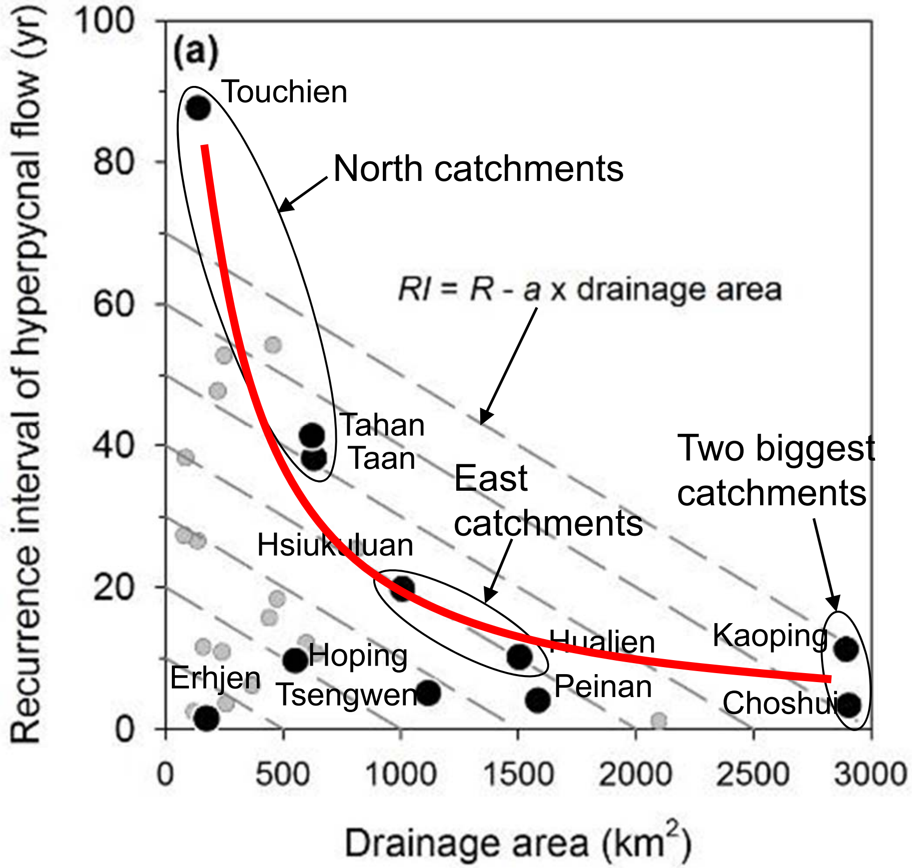
Catchments	drainage area (km^2)	runoff (km^3/yr)	Sediment discharge (Mt/yr)	Sediment yield (t/km^2/yr)	Recorded period	Days with sediment observations
Tahan River	622.80	1.12	29.28	47,015.69	1963-2006	1,273
Touchien River	139.07	0.31	***0.12***	849.02	1971-2005	1,025
Taan River	599.32	1.15	18.32	30,562.41	1972-2006	997
Tachia River	916.00	1.83	13.15	14,353.38	1979-2003	765
Choshui River	2,906.32	4.61	***93.81***	32,277.65	1987-2009	689
Tsengwen River	987.74	1.38	17.37	17,590.26	2000-2009	266
Erhjen River	175.10	0.30	15.53	***88,667.33***	1971-2008	883
Kaoping River	2,894.79	***7.06***	***65.04***	22,467.55	1991-2009	505
Linpien River	309.86	0.78	2.50	8,079.75	1961-2009	1,499
Hoping River	553.01	1.33	11.86	21,453.88	1975-2009	1,055
Hualien River	1,506.00	3.30	41.08	27,276.85	1969-2008	1,199
Hsiukuluan River	1,538.81	3.30	26.46	17,196.23	1969-2008	1,183
Peinan River	1,584.29	3.01	59.75	37,712.05	1948-2009	2,227

The outcrop of mudstone is the major reason to lead high sediment supply rate in Erhjen River.



Increase rate (Mt/km^3) = sediment discharge / runoff = 0.02 – 52.08

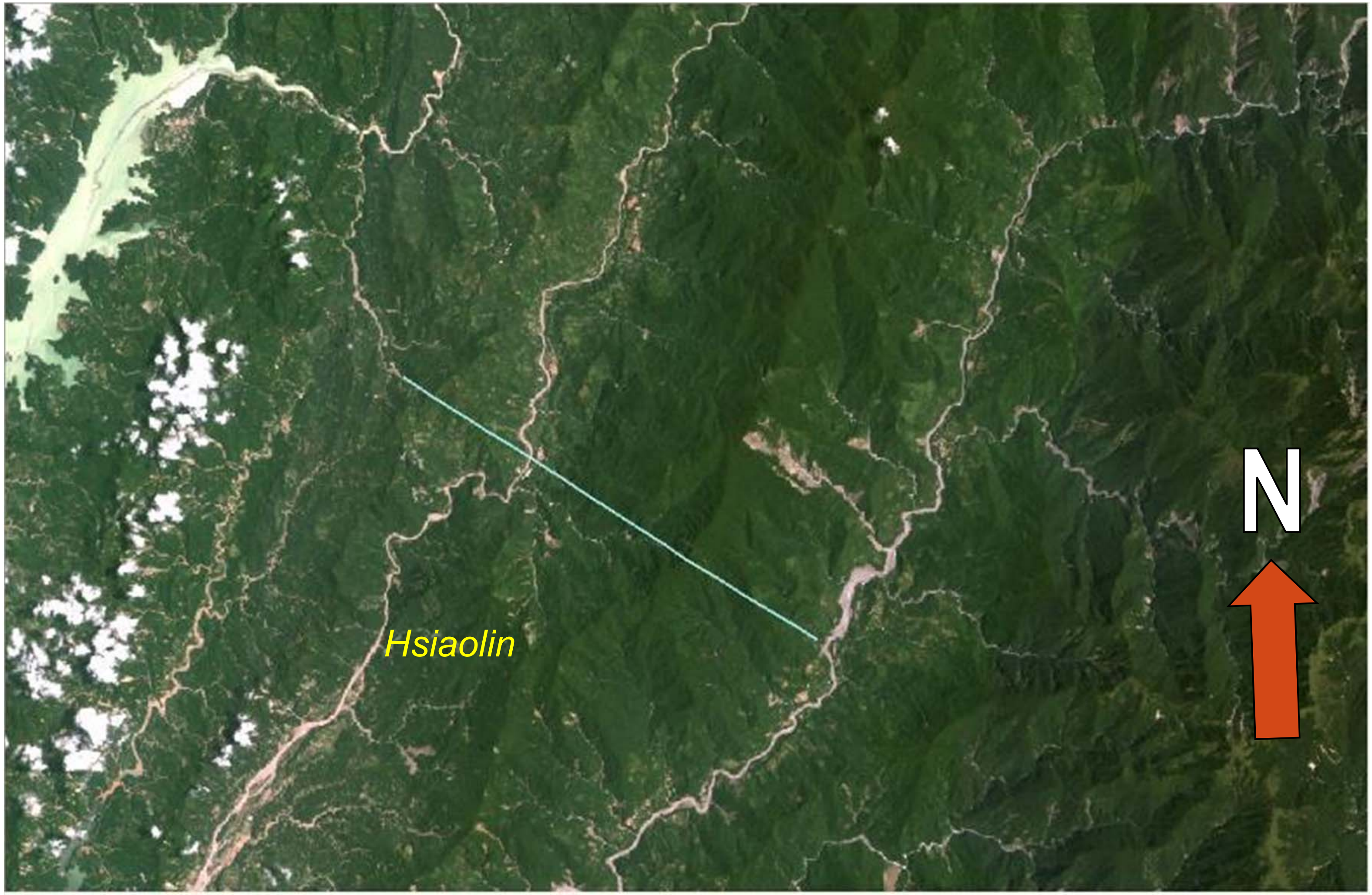




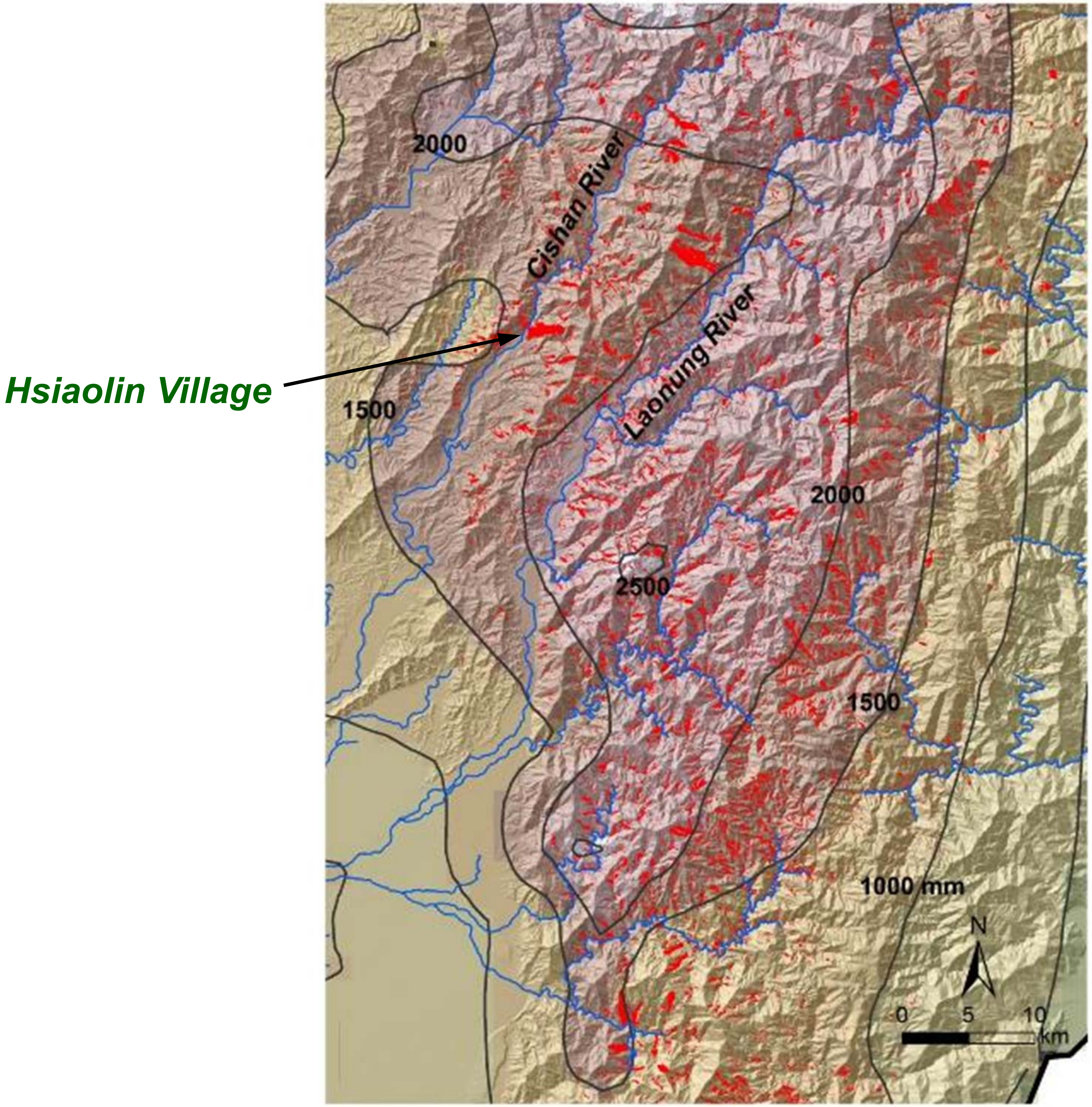
- Shorter recurrence intervals occur in catchments with bigger drainage areas.
- Abundant sediment sources should account for the high frequency of hyperpycnal flows in big catchments.

(3)Landslide mapping and analysis

The inventory of landslides was constructed by using remote sensing images taken before and after typhoons.



Map sources: Aerial Survey Office, Central Geological Survey, NCDR



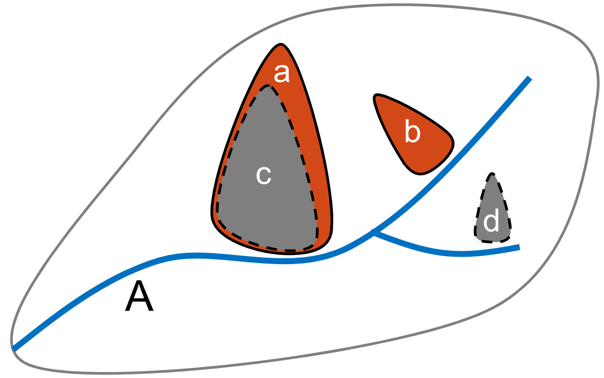
Most of landslides were located in the area with rainfall > 1000 mm.

(3)Landslide mapping and analysis

$$\text{Landslide ratio} = \frac{\text{Total landslide area}}{\text{Study area}} \times 100\% = \frac{a+b+c}{A}$$

$$\text{Reactivated ratio} = \frac{\text{Reactivated landslide area}}{\text{Total landslide area of previous event}} \times 100\% = \frac{c}{c+d}$$

$$\text{New generation ratio} = \frac{\text{New landslide area}}{\text{Total landslide area}} \times 100\% = \frac{a+b}{a+b+c}$$



Catchments	Landslide ratio (%)	New generation ratio (%)	Reactivated ratio (%)	Record period	Recorded typhoon number	Recorded cumulative rainfall (mm)
Tahan River	1.34 ± 0.79	75.88 ± 15.59	*23.93 ± 17.21*	1985-2009	6	456-996
Touchien River	*0.89 ± 0.37*	76.20 ± 4.78	26.68 ± 10.32	1996-2009	7	321-984
Tana River	2.60 ± 0.73	49.30 ± 9.36	52.63 ± 16.38	1996-2009	5	497-1057
Tachia River	*9.26 ± 3.91*	54.20 ± 6.19	52.37 ± 9.03	1996-2009	9	266-1157
Choshui River	4.84 ± 2.58	61.03 ± 11.74	49.42 ± 26.98	1996-2009	5	479-1311
Tsengwen River	5.88 ± 1.18	36.55 ± 10.57	*69.86 ± 10.37*	1996-2009	9	101-1762
Erhjen River	*10.05 ± 4.77*	-	-	1987-2009	-	-
Kaoping River	3.29 ± 2.05	45.24 ± 13.40	54.76 ± 13.40	1996-2009	6	274-1920
Linpien River	2.68 ± 3.07	*96.11 ± 48.01*	47.33 ± 23.67	2001-2009	3	113-1219
Hoping River	2.50 ± 1.25	-	-	2001-2009	2	267-507
Hualien River	1.88 ± 0.10	64.70 ± 11.14	44.86 ± 5.69	2008-2009	2	166-369
Hsiukuluan River	1.18 ± 0.73	*25.56 ± 12.78*	33.54 ± 16.77	2001-2009	2	266-488
Peinan River	1.89 ± 0.93	55.16 ± 18.54	54.35 ± 9.75	1999-2009	11	262-1191

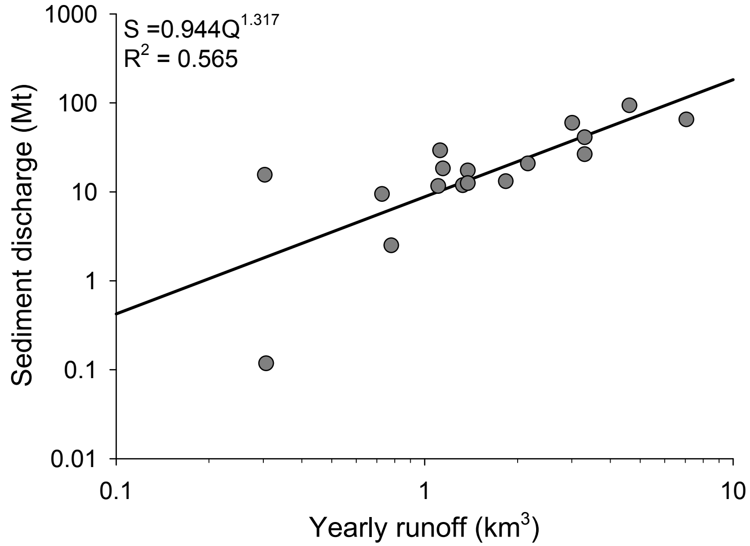
- The highest landslide ratios are in *Erhjen* and *Tachia catchments*.
- The highest new generation ratio is in *Linpien catchment*.
- The highest reactivated ratio is in *Tsengwen catchment*.

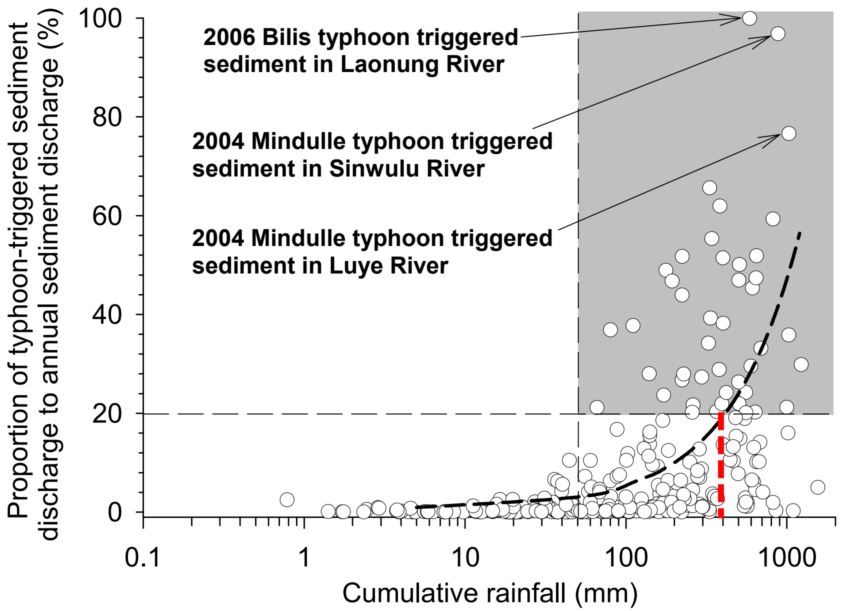
Influences on landsliding and sediment discharge

1. *Rainfall and Runoff*
   — *Weather Radar Application*
2. *Rock properties*
   — *Rock strength*
   — *Joint density*
3. *Earthquake*
4. *Human activities*

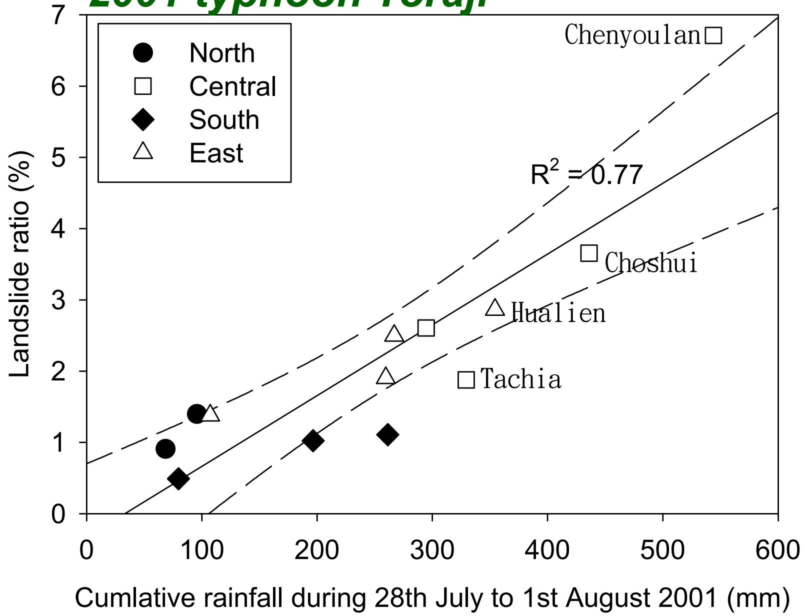
Effect I: Runoff / Rainfall

- Sediment discharges and landslides have power-law relationships with *rainfall* and *runoff*.
- Sediment discharge induced by typhoons with rainfall > *400 mm* would occupy more than *20 %* of annual sediment discharge.



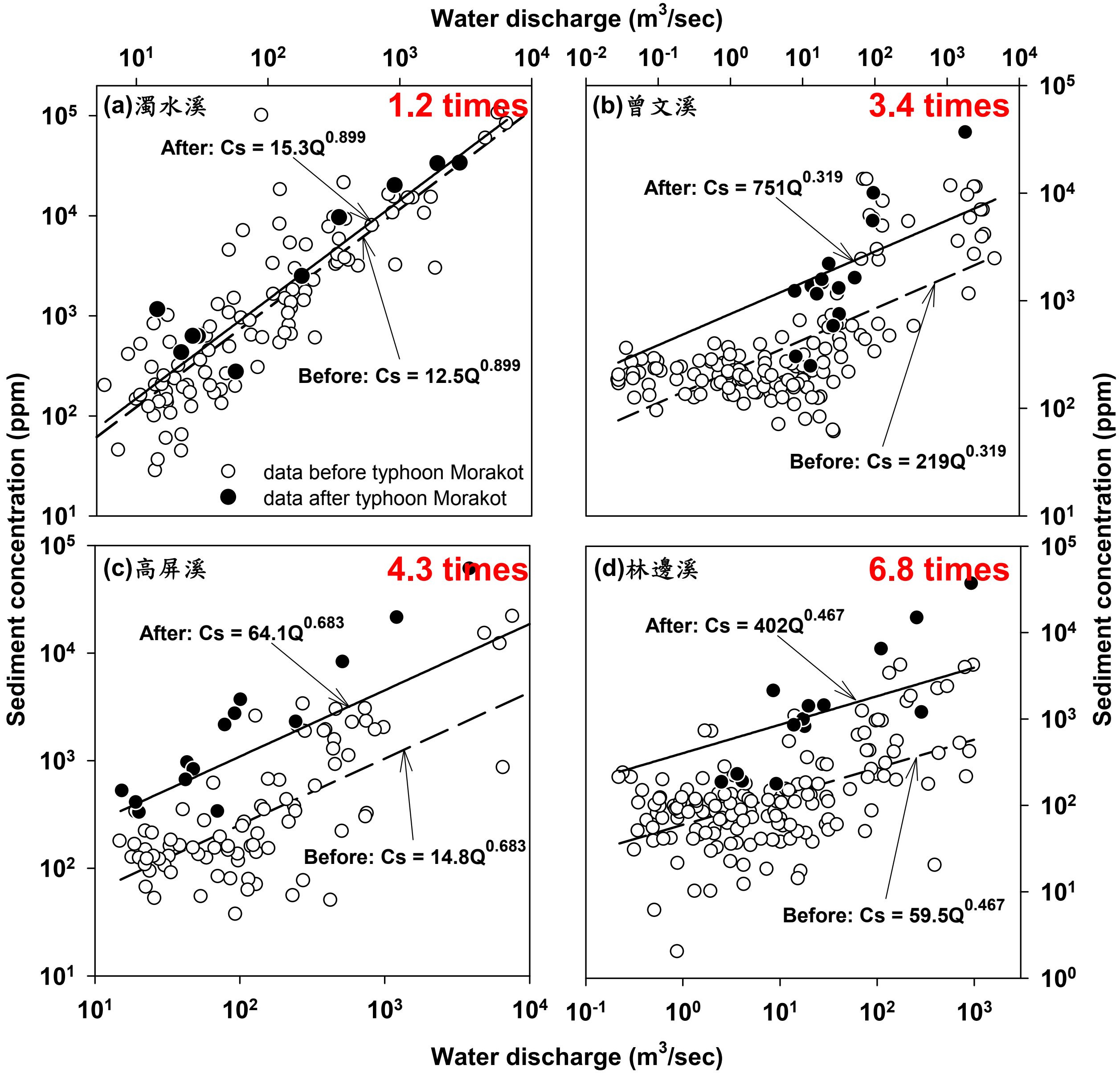


2001 typhoon Toraji



Impact of Morakot typhoon

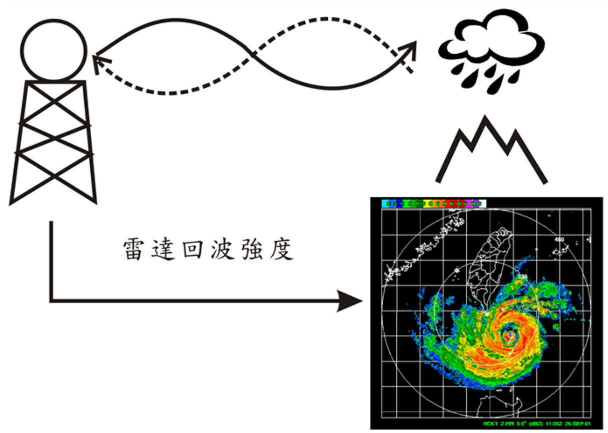
$Cs = \kappa Q^b$

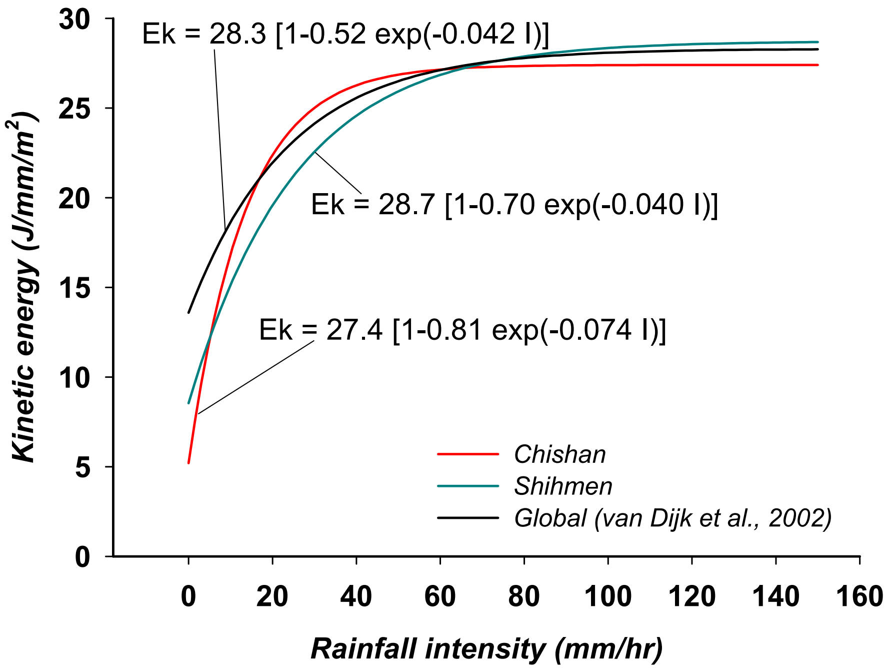


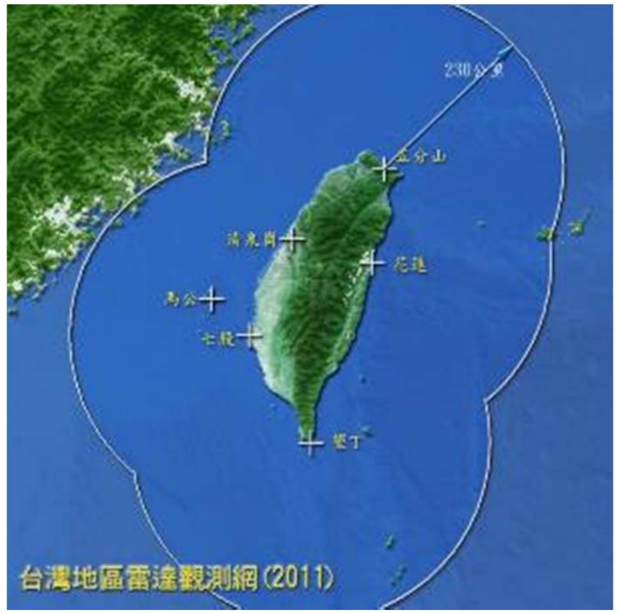
Impact of Morakot typhoon increased form north region to south region (coincided with rainfall)

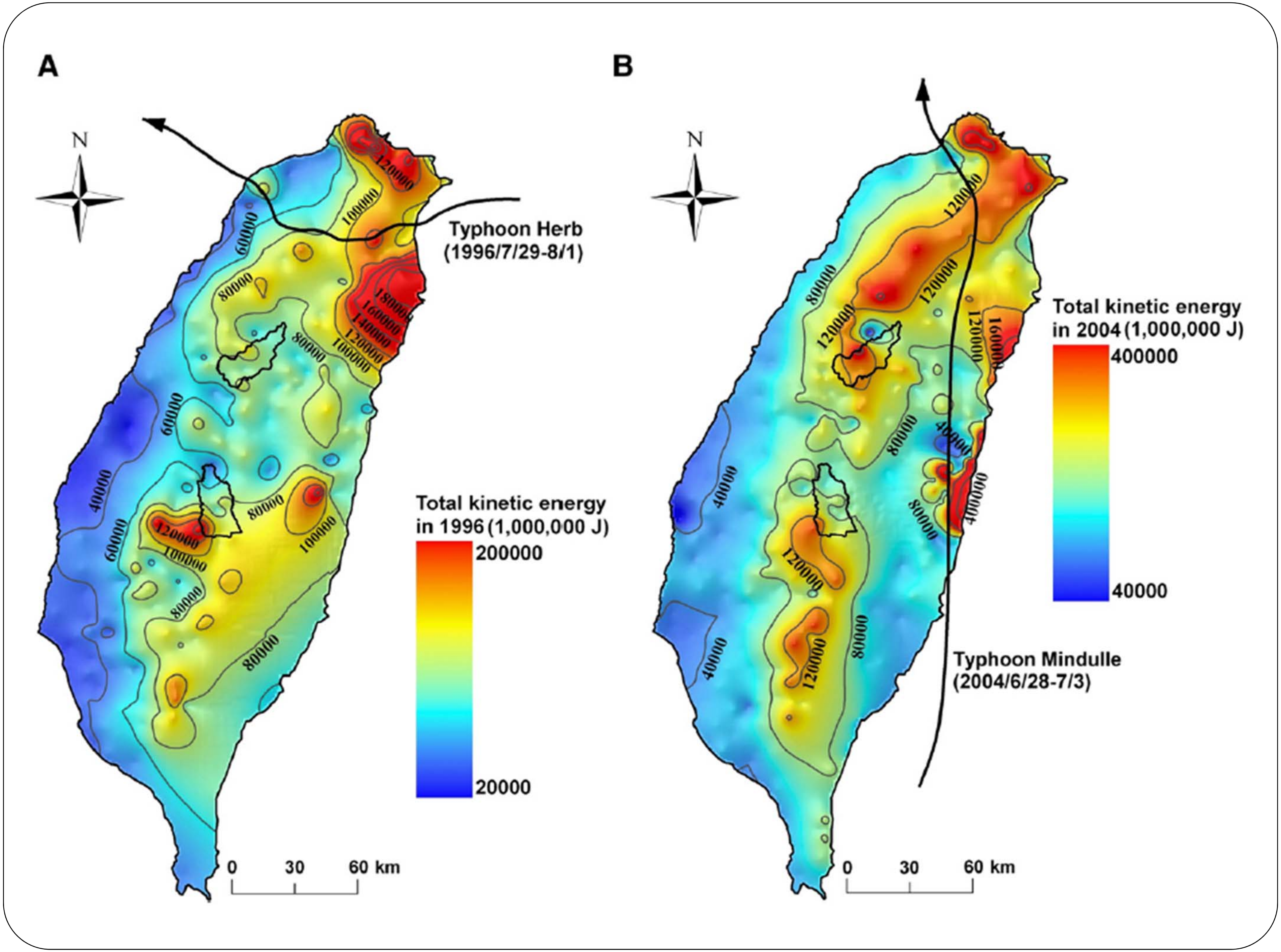
Radar technology → Rainfall information

- Traditional rain gauge observation only provides point information.
- Weather radars provide spatial variation of rainfall information.

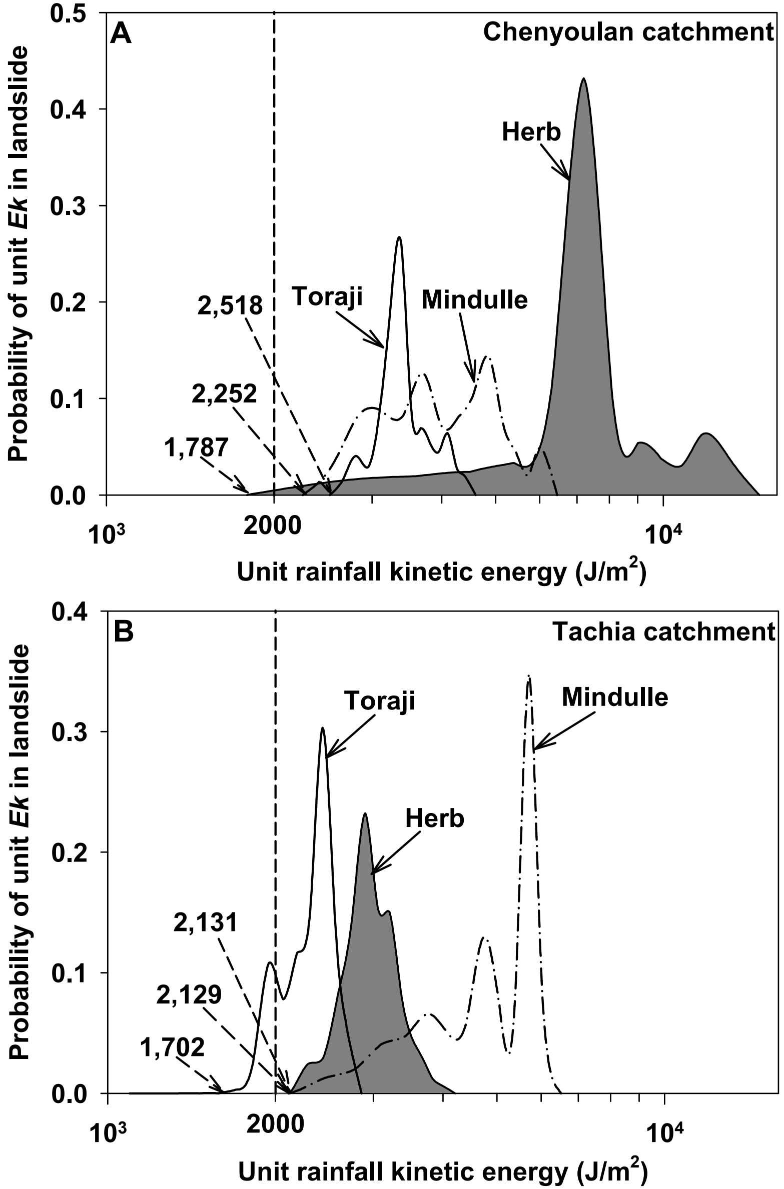


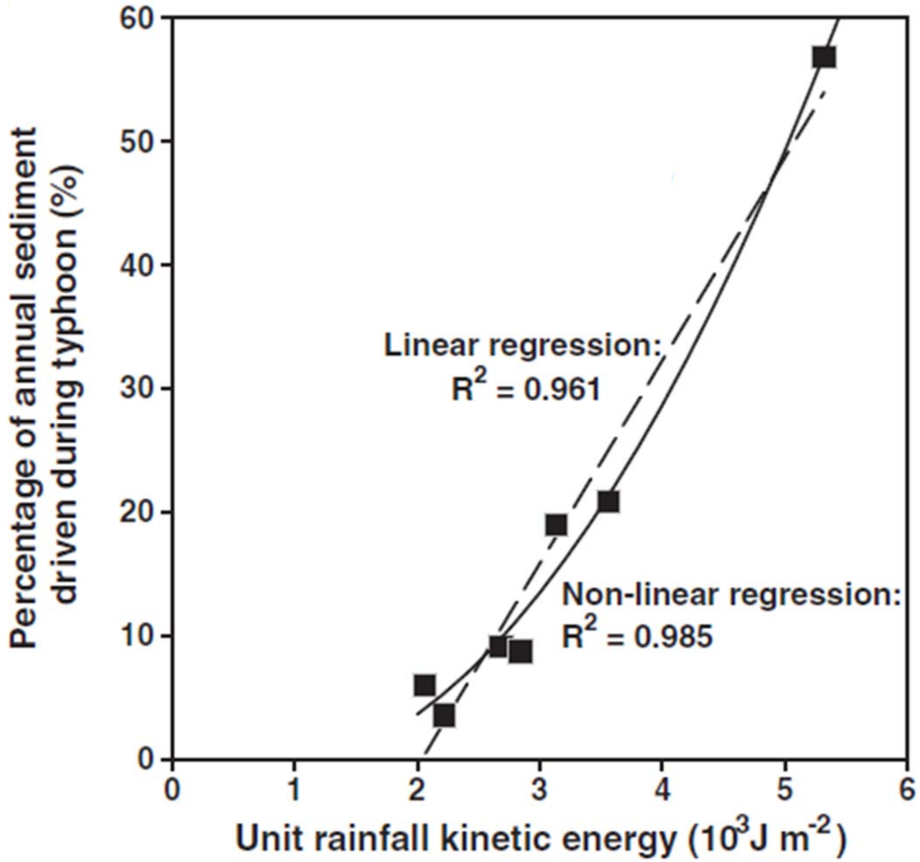





A
B
N
Typhoon Herb
(1996/7/29-8/1)
Total kinetic energy
in 1996 (1,000,000 J)
200000
20000
Total kinetic energy
in 2004 (1,000,000 J)
400000
40000
Typhoon Mindulle
(2004/6/28-7/3)
0 30 60 km

Impact of Rainfall Energy

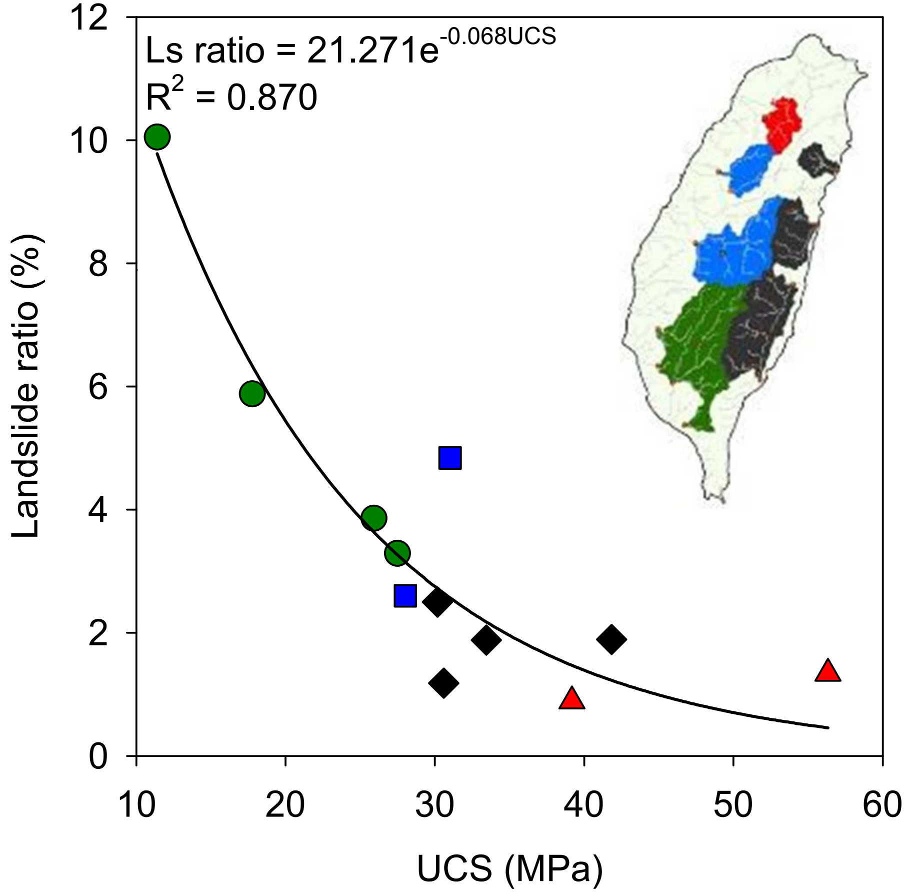


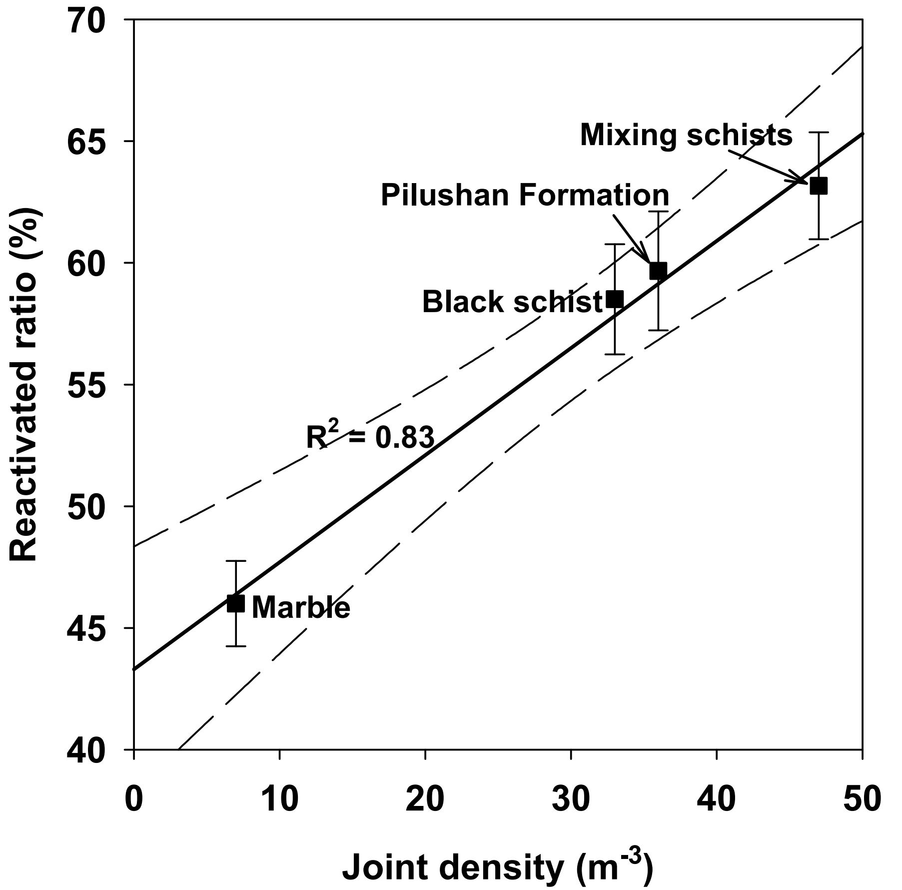


Perhaps rainfall energy can be an index to predict landsliding or sediment discharge.

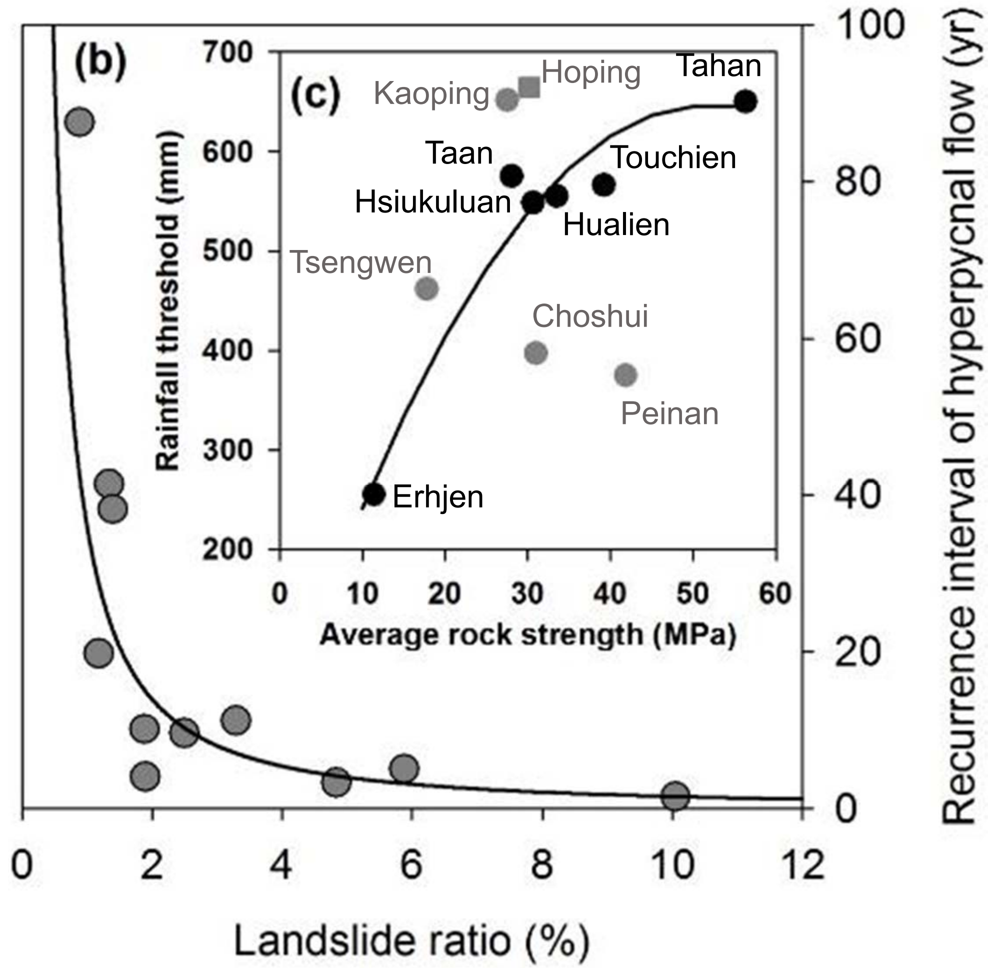
Effect II: Rock Properties

- The areas affected by landslides are less in the catchments having higher rock strength.
- Landslides are prone to be reactivated in the formations having higher joint density.



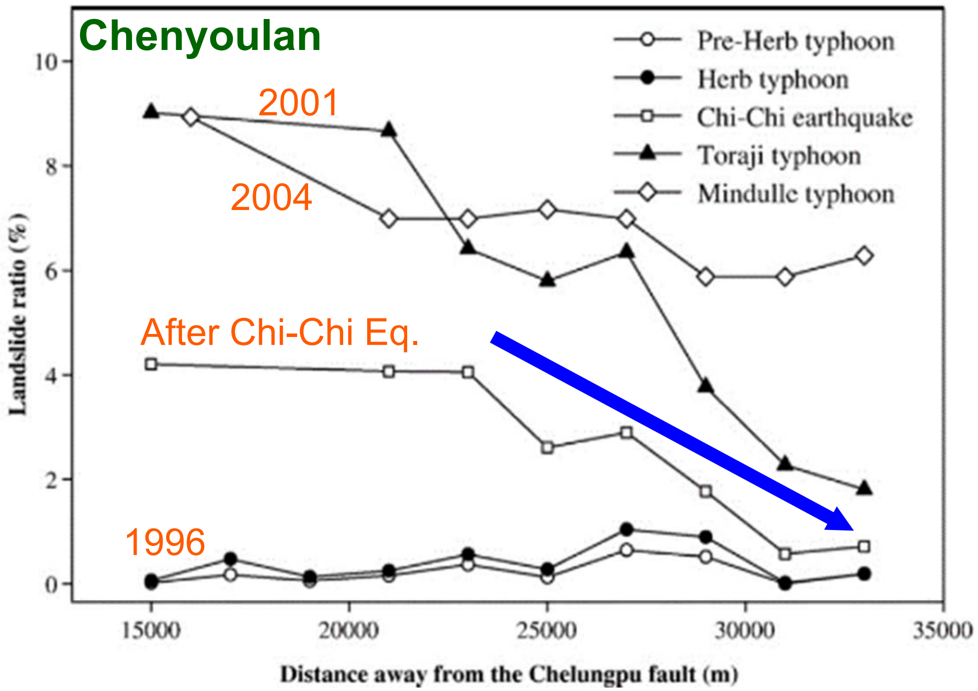


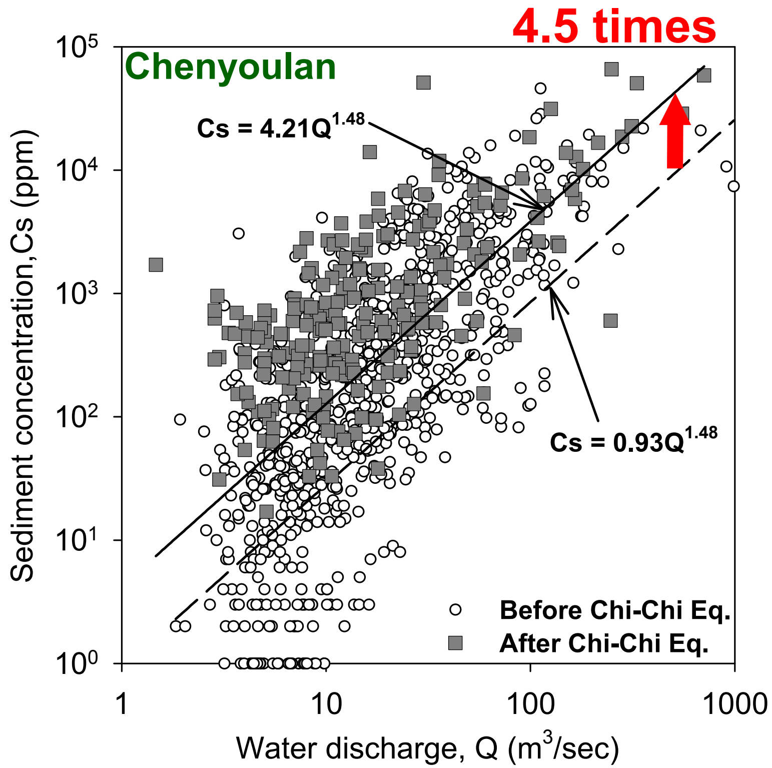
Rock properties would affect landslide occurrence and types.



- Turbidity-flow concentrations are prone to occur in catchments which have a lot of landslides to supply sediment to channel.
- Higher rainfall is required to form turbidity-flow concentration in catchments with high rock strength, and also confirms that turbidity-flow concentration rarely occurs in catchments with limited supply sources of suspended sediment from landsliding.

Effect III: Earthquake

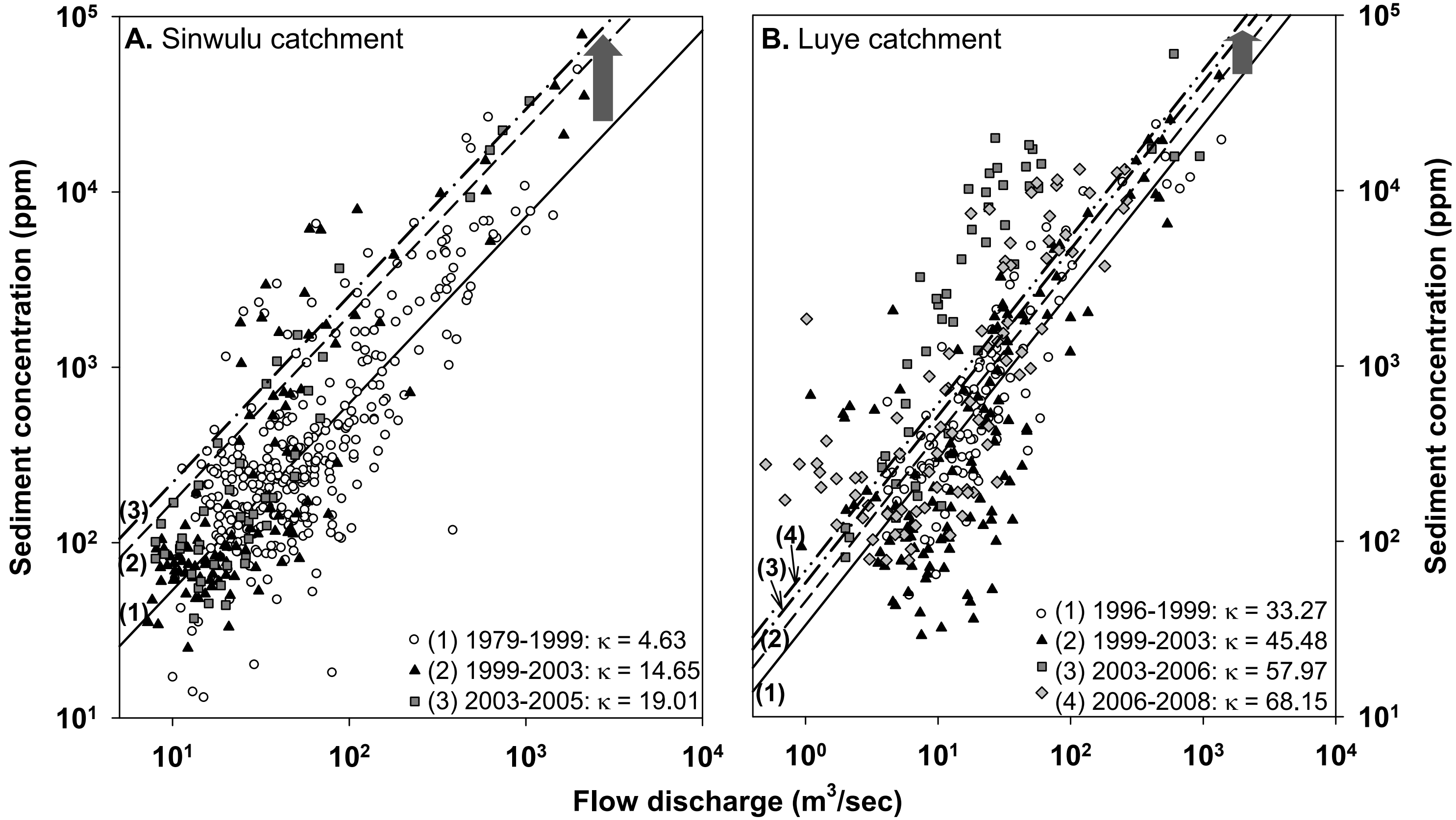




$Cs = \kappa Q^b$

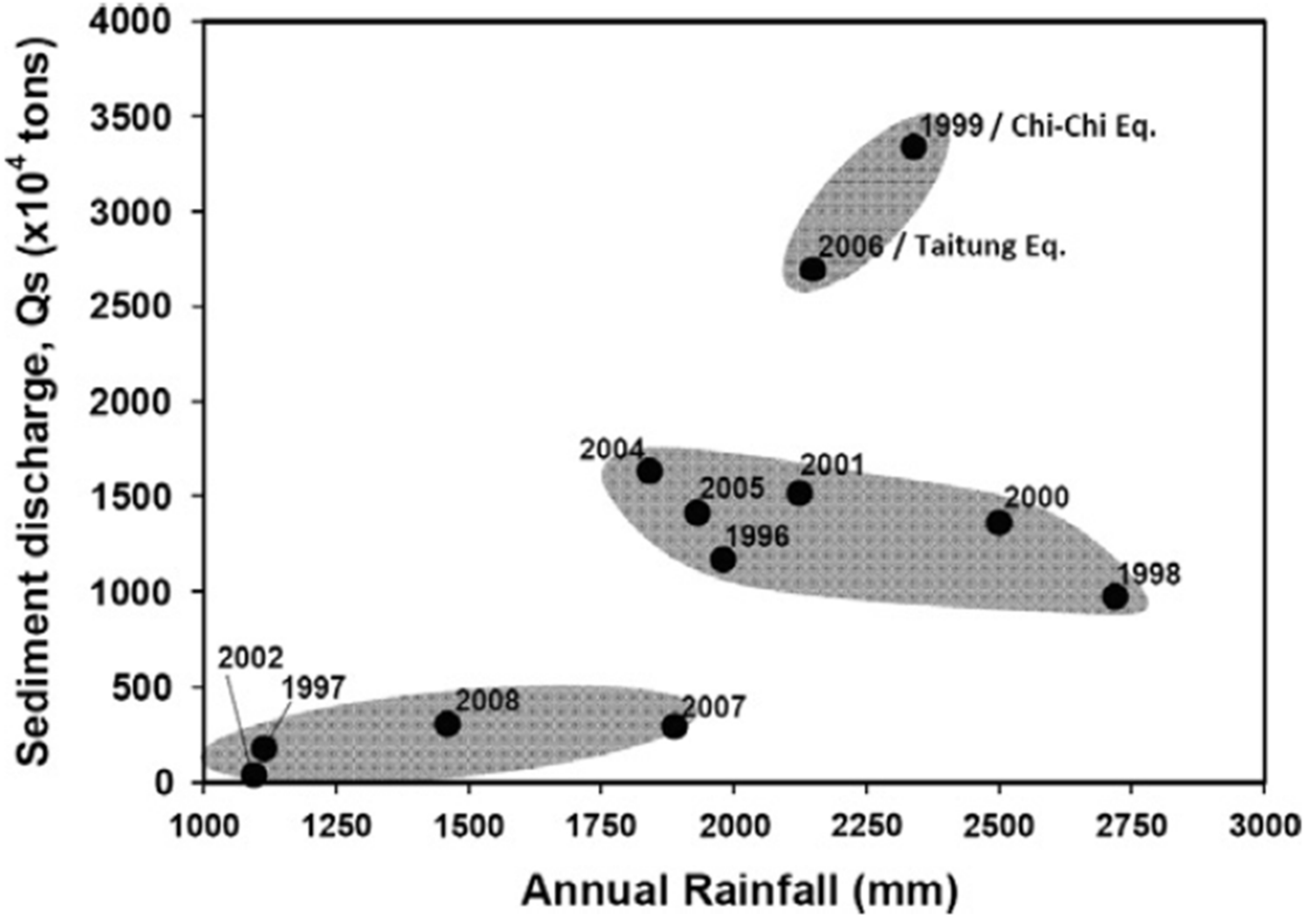
Higher landslide possibility as closer to earthquake fracture zone.
Eq. impact seems become less significant in 2004.

$Cs = \kappa Q^b$



- ***2003/12/10 Chengkung earthquake*** and ***2006/4/1 Taitung earthquake*** affected the sediment yielding in the Peinan catchments.

Sediment discharge in Luye River (tributary of Peinan River)



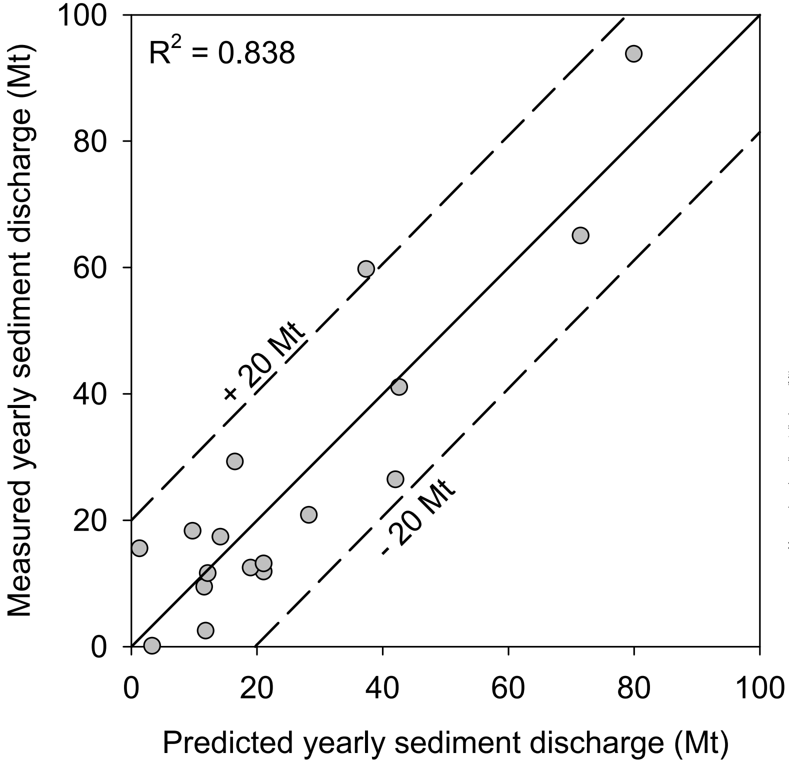
Peak annual sediment discharge occurred after earthquakes.
The combination of Eq. and high annual rainfall results in high annual sediment discharge.

Regression relationship of factors

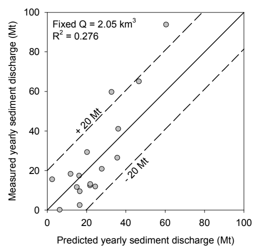
$$S = 0.625\, Q^{1.359}\, UCS^{-0.787}\, Jv^{1.502}\, Eq$$

S: annual sediment discharge (Mt)
Q: yearly runoff (km^3)
UCS: uniaxial compressive strength (MPa)
Jv: number of discontinuity per cubic meter (m^{-3})
Eq: earthquake frequency (yr^{-1})

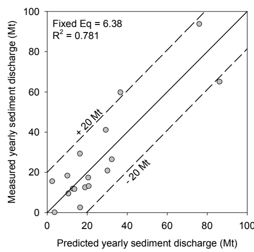
Alteration of R^2 when removing a factor from multivariate regression reflects the efficiency.



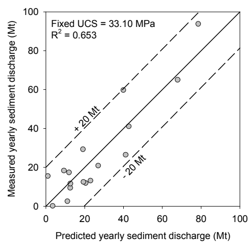
Factors	R^2	ΔR^2	Efficacy (%)
$S = 0.625Q^{1.359}UCS^{-0.787}Jv^{1.502}Eq$	0.838	-	83.8
Yearly Runoff (Q)	0.276	0.562	**56.2**
Uniaxial compressive strength (UCS)	0.653	0.185	18.5
Joint density (Jv)	0.804	0.034	3.4
Earthquake frequency (Eq)	0.781	0.057	5.7



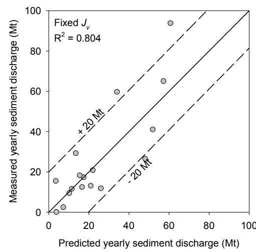
Fixed Q
$R^2 = 0.276$



Fixed Eq
$R^2 = 0.781$



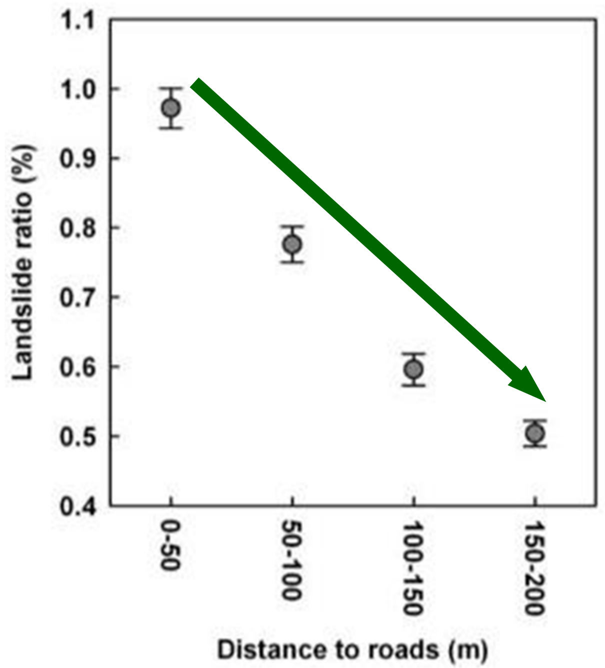
Fixed UCS
$R^2 = 0.653$



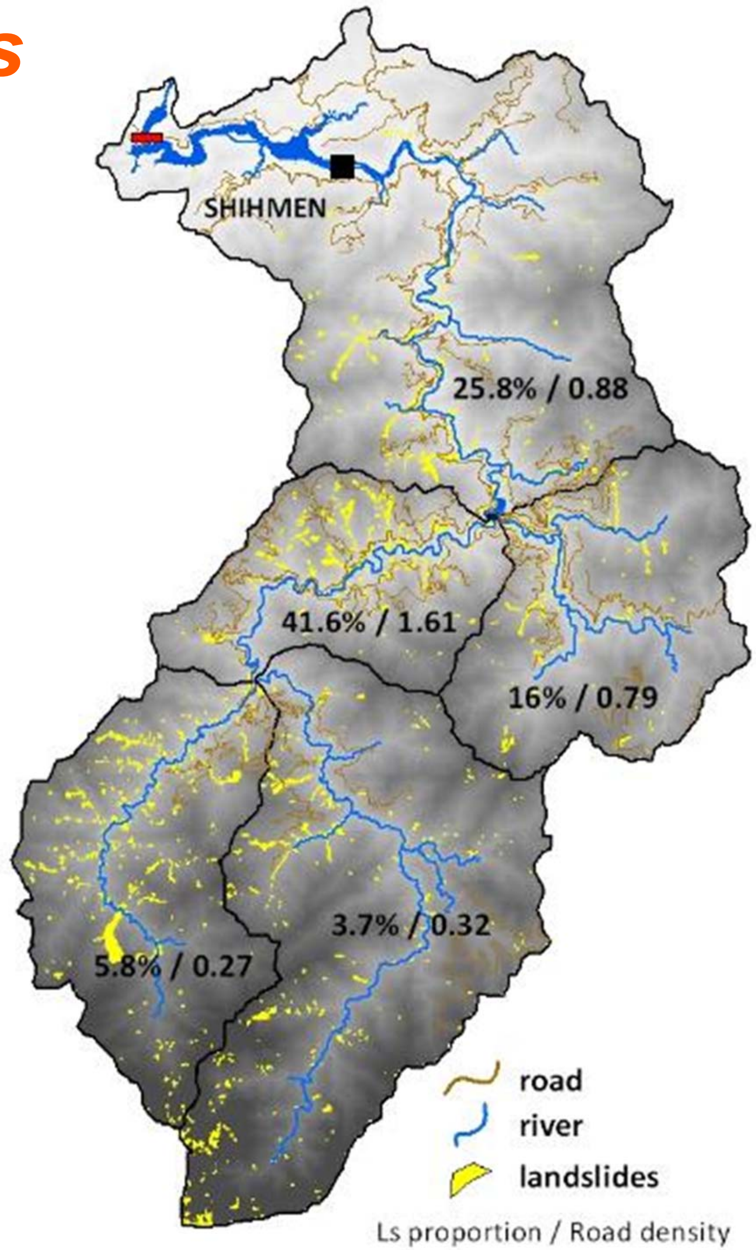
Fixed Jv
$R^2 = 0.804$

Rest of efficiency can be attributed to human activities, climate, etc.

Effect of human activities



- 3% - 42% of landslides are located along the both sides of roads.
- Slope stability has some relations with road density.

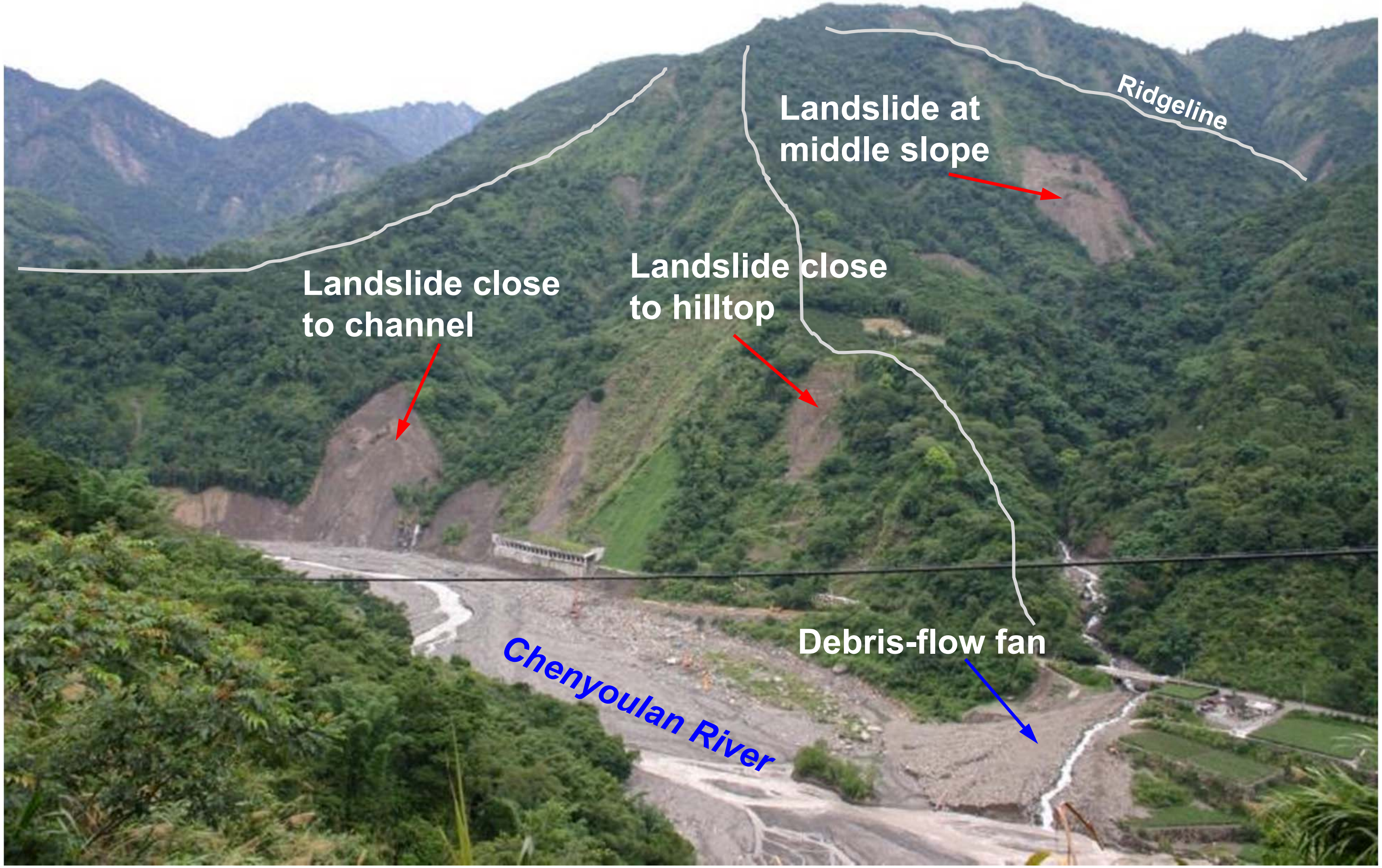


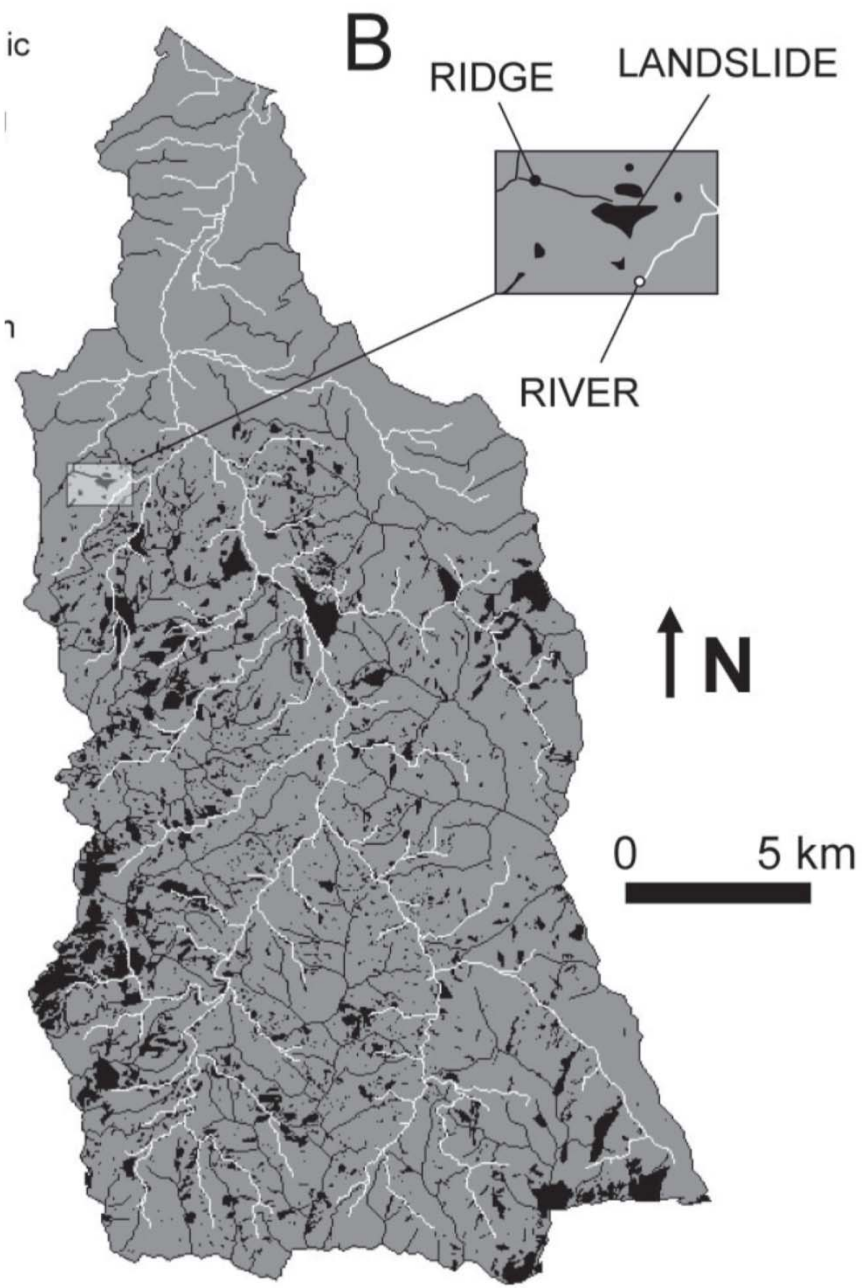

Road construction would be a significant impact on slope stability.


Landslide
Road
Check dam

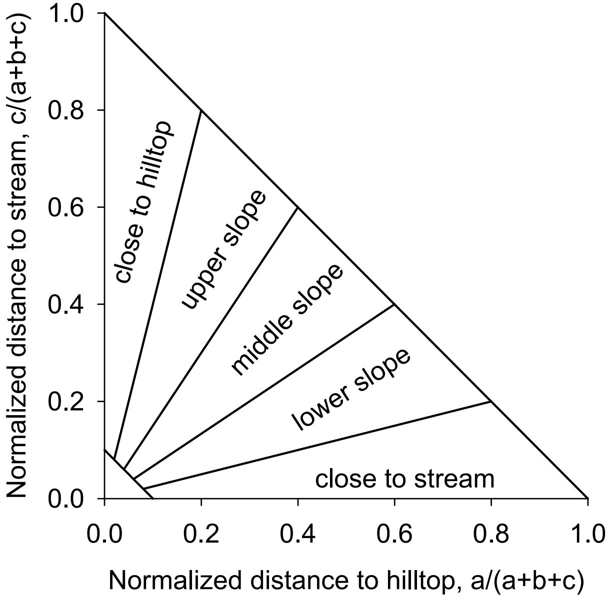
Human effect on landsliding is obvious and serious.

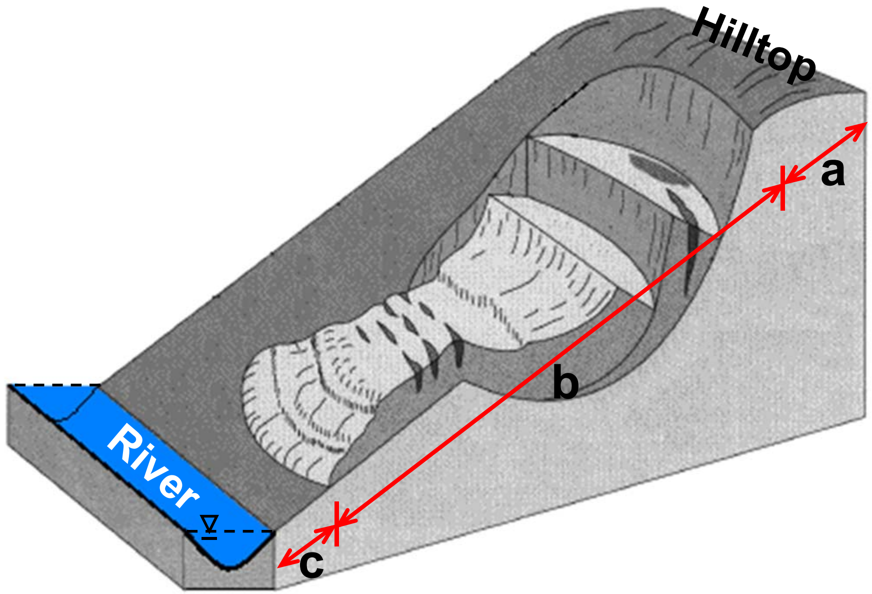
Discussions (1): Links between landslide location and rivers

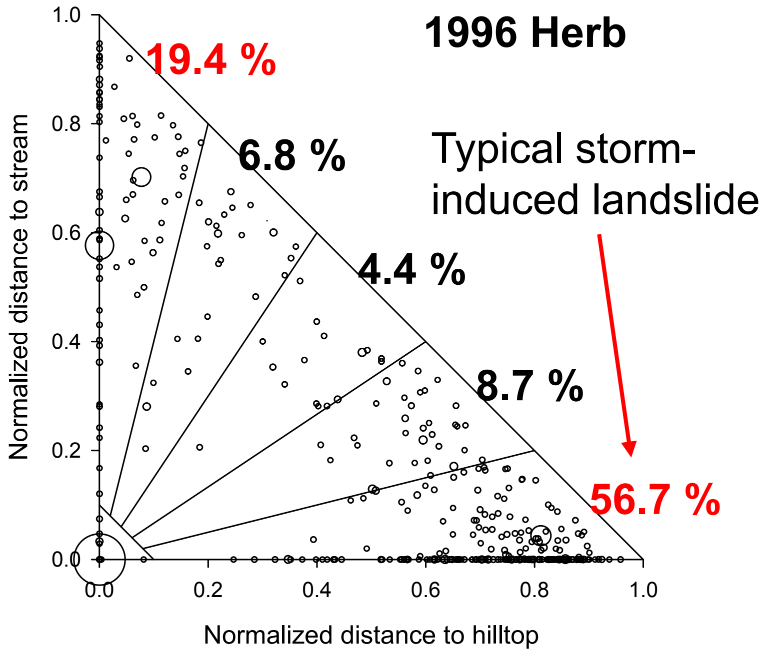


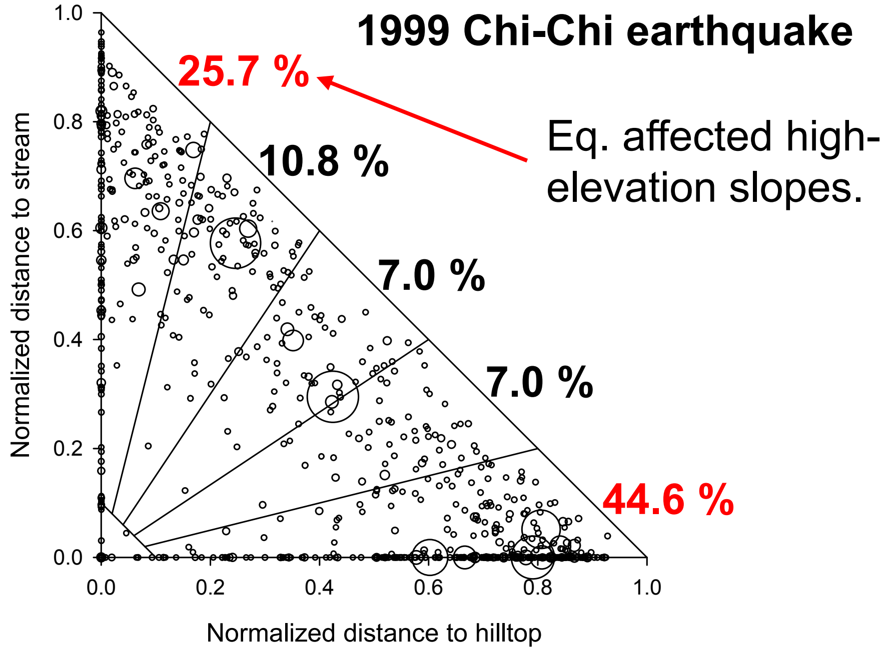

B
RIDGE
LANDSLIDE
RIVER
N
0
5 km

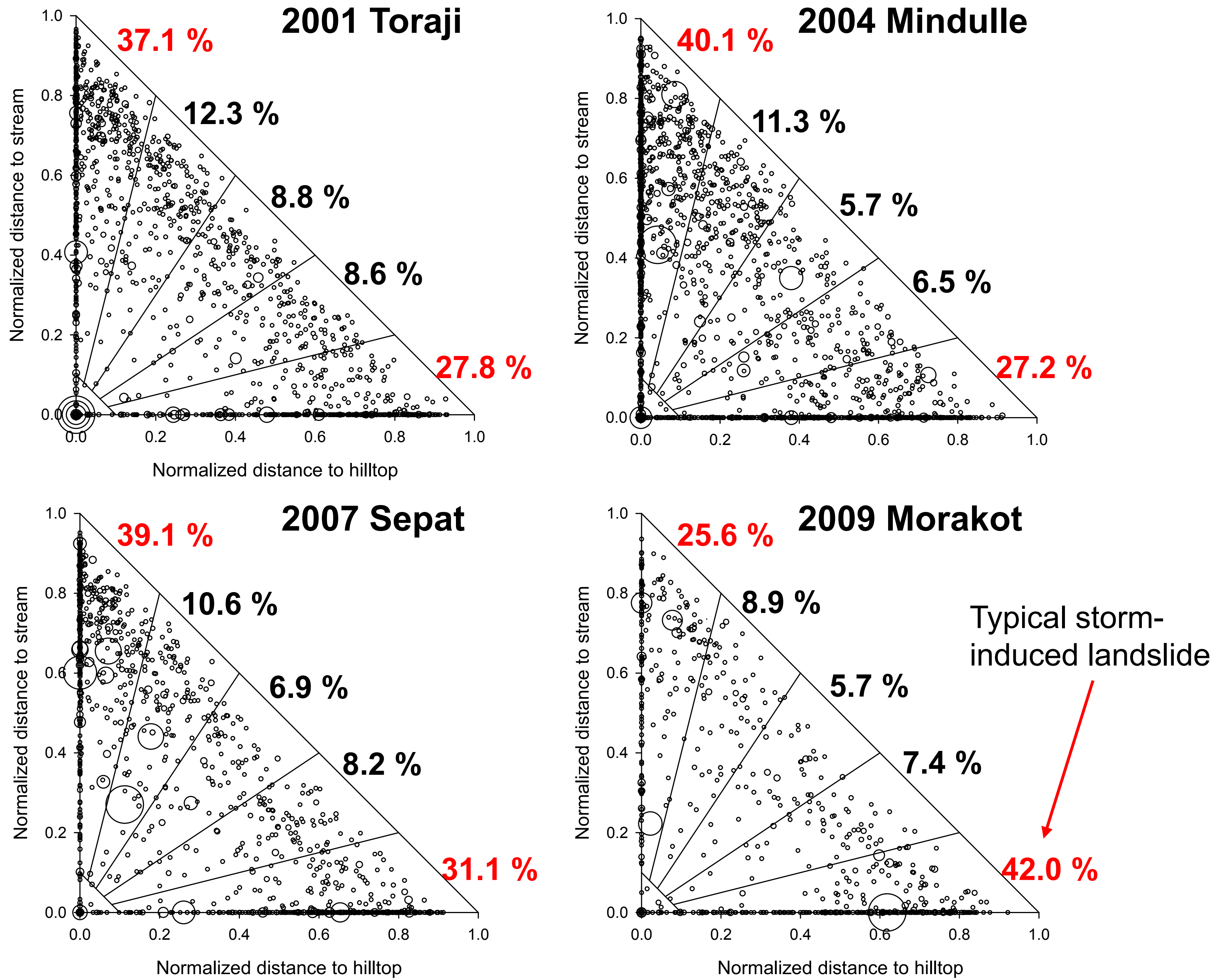
Landslide location



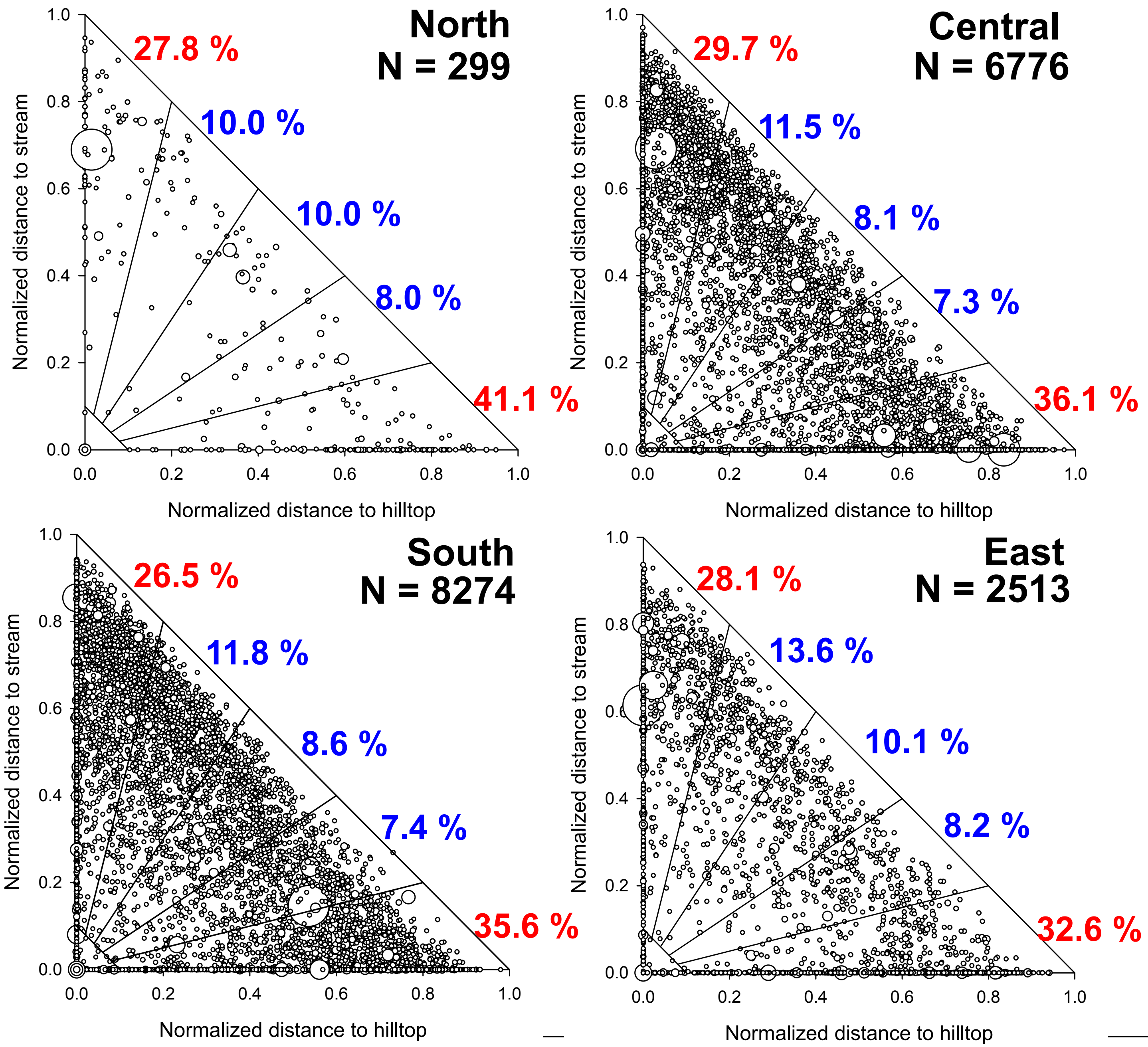




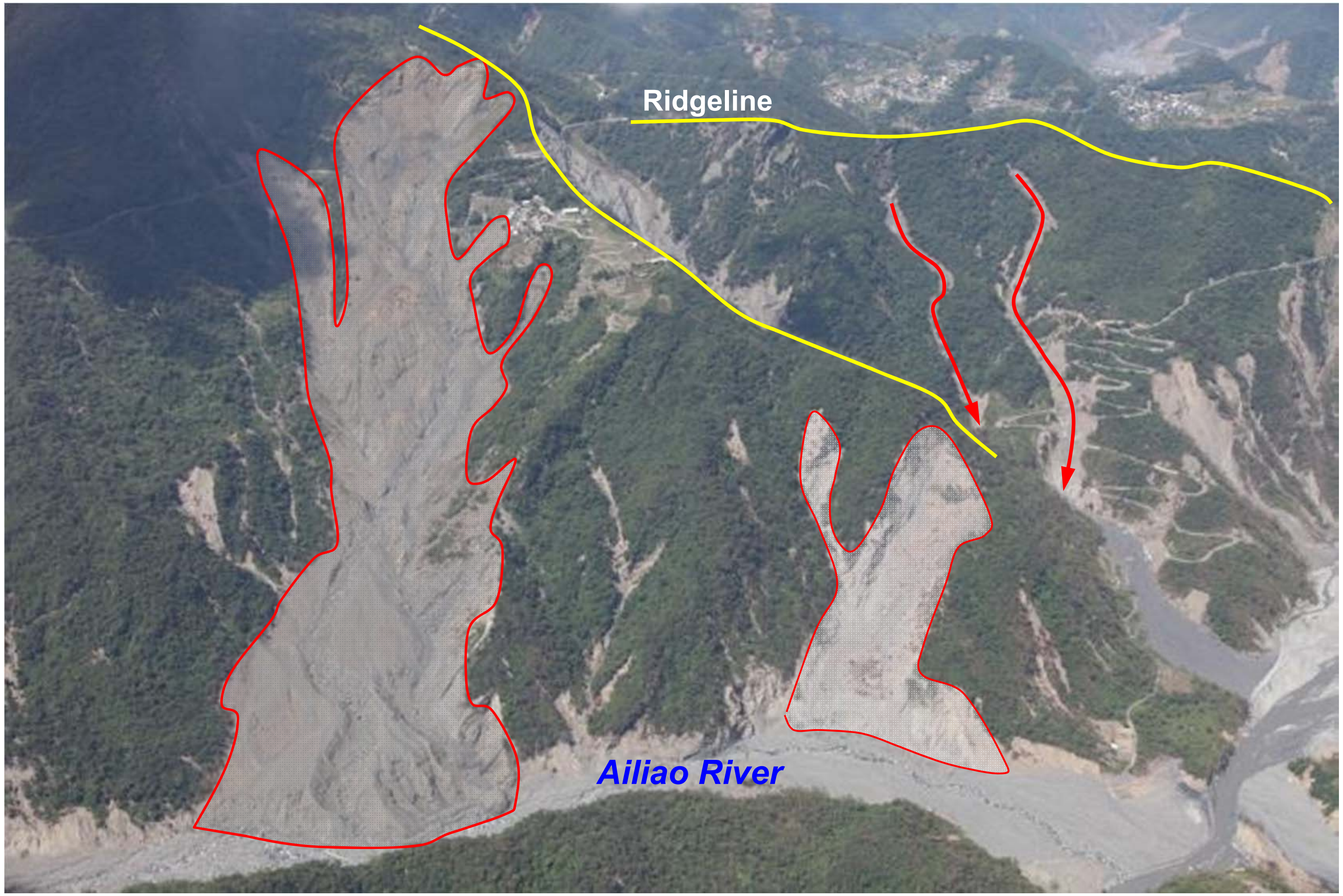



2001 Toraji
37.1 %
12.3 %
8.8 %
8.6 %
27.8 %
2004 Mindulle
40.1 %
11.3 %
5.7 %
6.5 %
27.2 %
2007 Sepat
39.1 %
10.6 %
6.9 %
8.2 %
31.1 %
2009 Morakot
25.6 %
8.9 %
5.7 %
7.4 %
42.0 %
Typical storm-induced landslide
Normalized distance to stream
Normalized distance to hilltop
0.0
0.2
0.4
0.6
0.8
1.0

Landslide triggered by 2009 Morakot typhoon (Typical storm-induced landslide)



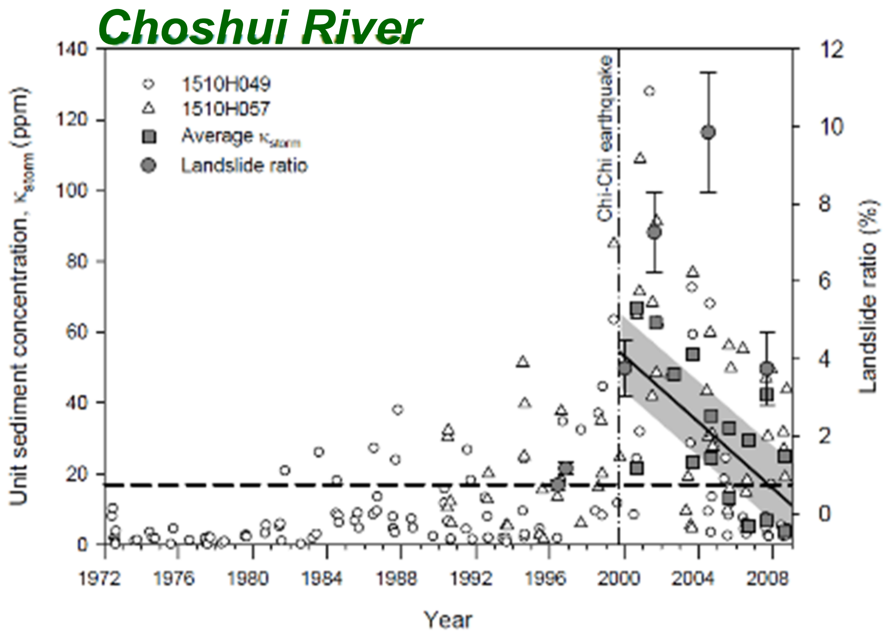
After 2009 Morakot typhoon, a lot of landslides were distributed along the river channel and stretched toward hilltop. The combination of heavy rainfall and river discharge resulted in the occurrence of big landslides.

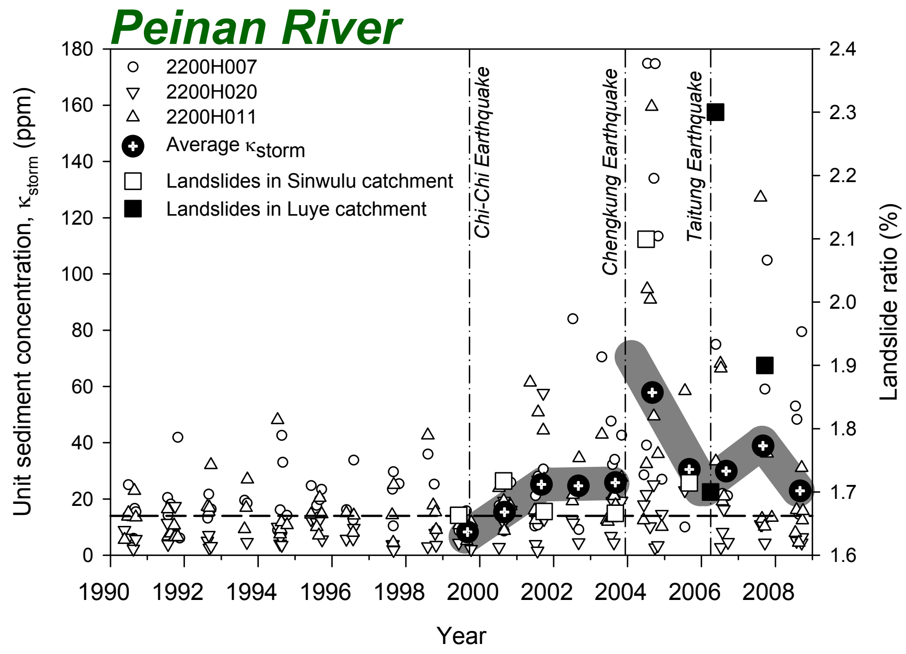


Discussion (2): Recovery period of sediment discharge after earthquake

August 2004

September 2008





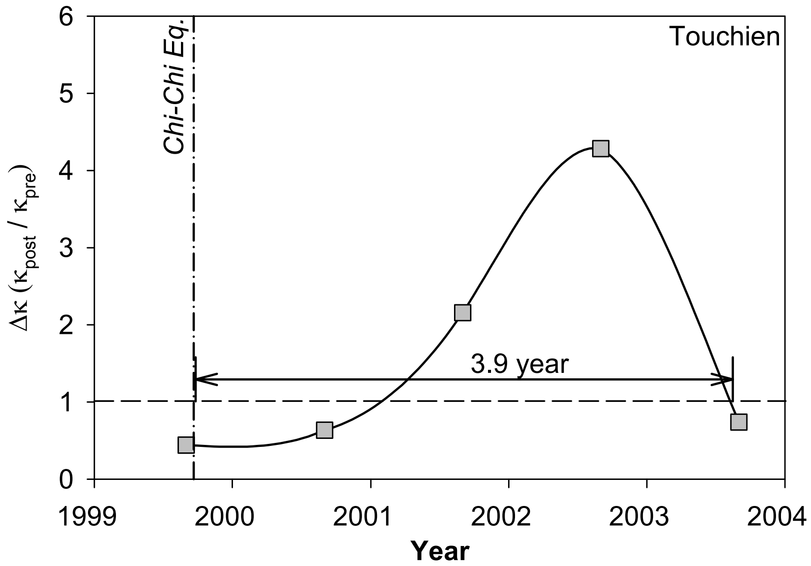
$$C_{storm} = \kappa_{storm} \times Q^b$$

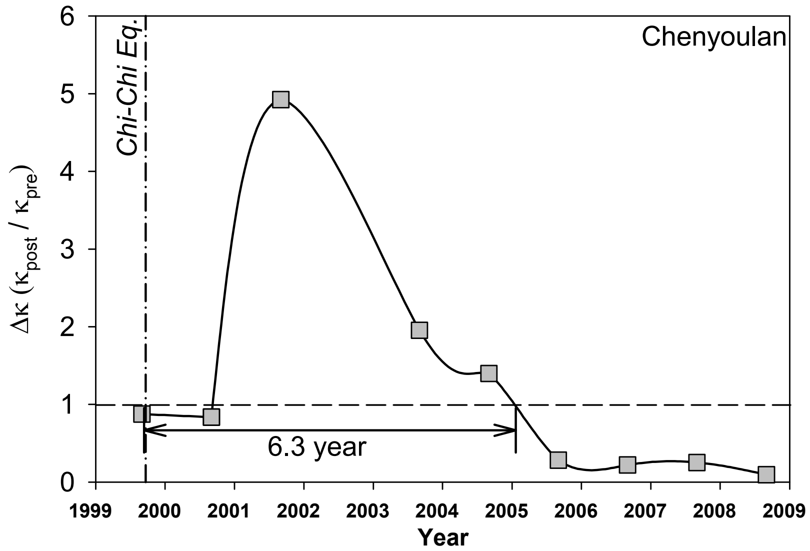
κ_{storm}: unit sediment concentration during storm.

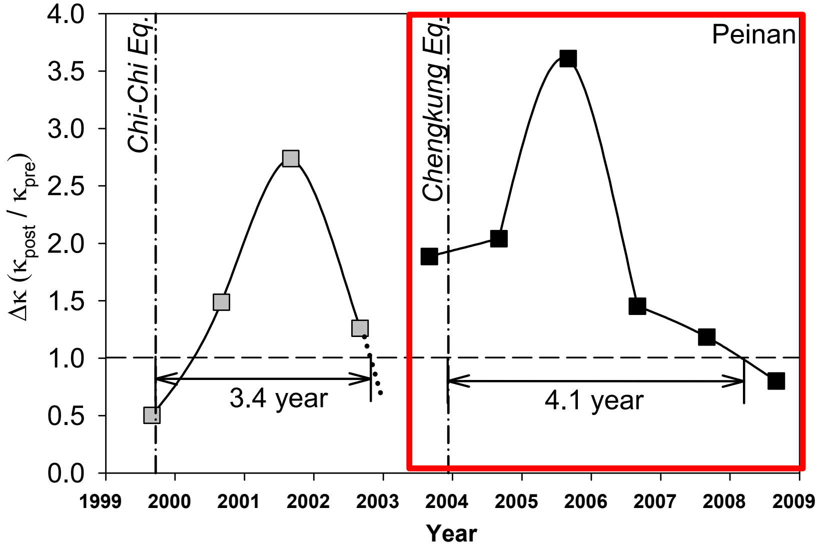
Average κ_{storm}: mean of all κ_{storm} in a given year.

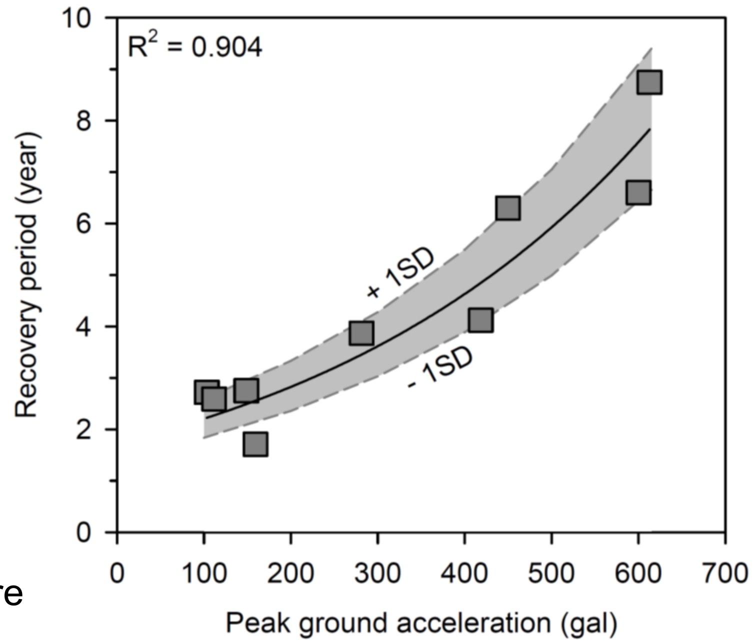
- The average κ_{storm} jumped after big earthquake, starting to decay to the original average calculated with data prior to 1999.
- In the Choshui catchment the impact of Chi-Chi earthquake may be consumed after 2008 by a sequence of rainstorms.
- Different Eq. resulted in different impact on κ_{storm}.

Recovery period of sediment discharge after earthquake









We have to avoid the disturbances from 2 and even more earthquakes.

Conclusions

- ***Relationships between sediment discharge, landslides, rock properties, rainfall, and earthquake:***

1. There are well relations between sediment discharge, rainfall and runoff. Sediment discharge induced by typhoons with rainfall ***> 400 mm*** would occupy more than ***20 %*** of annual sediment discharge.
2. Rock mass with ***higher rock strength*** and ***lower joint density*** could resist landsliding and sediment yielding. Geomaterial properties affect the rainfall threshold for turbidity flows.
3. Increasing landslide rate near roads reflects the impact of human activities.
4. The efficacy of runoff, rock properties, and earthquake was evaluated:

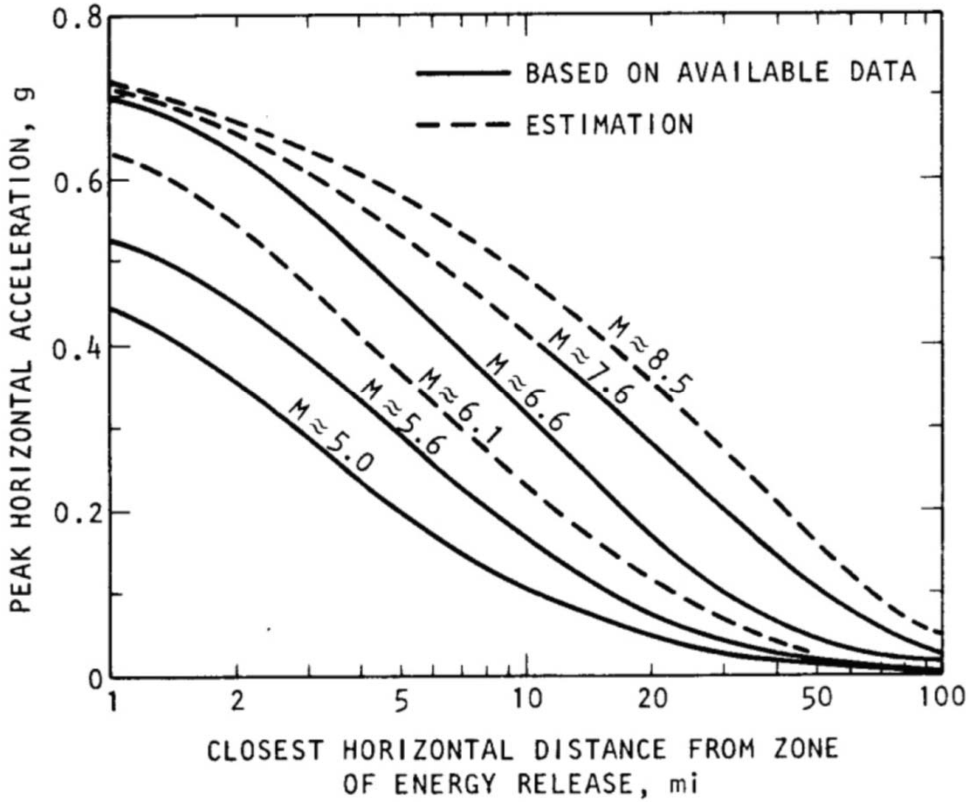
Runoff > Rock properties > earthquake

- ***Recovery period after earthquake:***

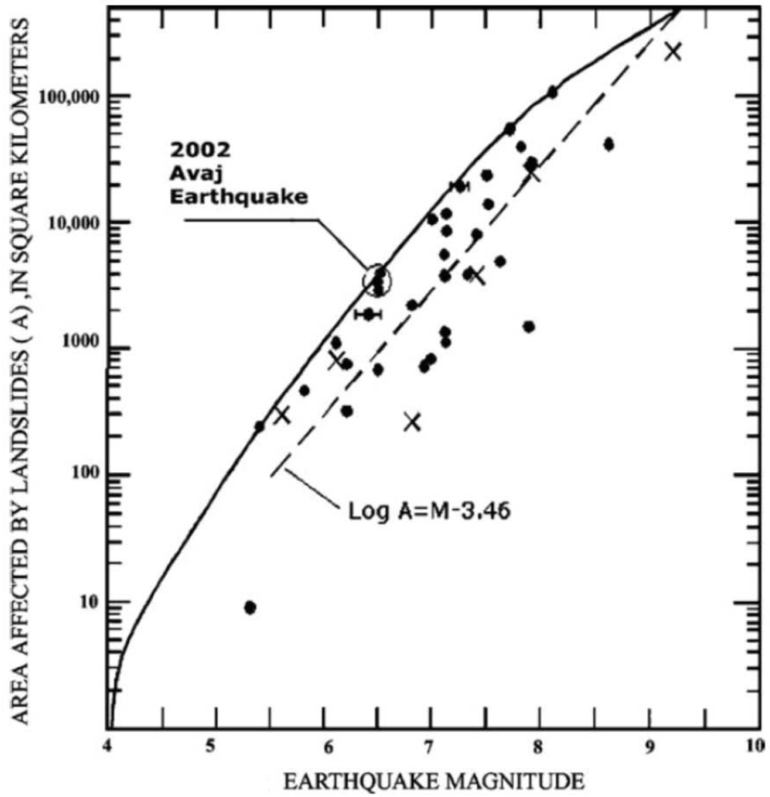
1. Earthquake will cause that landslides are distributed away from streams and prolong the duration of consumption of landsliding debris.
2. A extreme rainstorm will lead to big landslides stretching from hilltop to channel.
3. The recovery period of sediment discharge would be more than ***4 years*** as the catchments are disturbed by earthquake with peak ground acceleration ***> 400 gal***.

Thanks

We deeply appreciate the effort from Water Resources Agency.



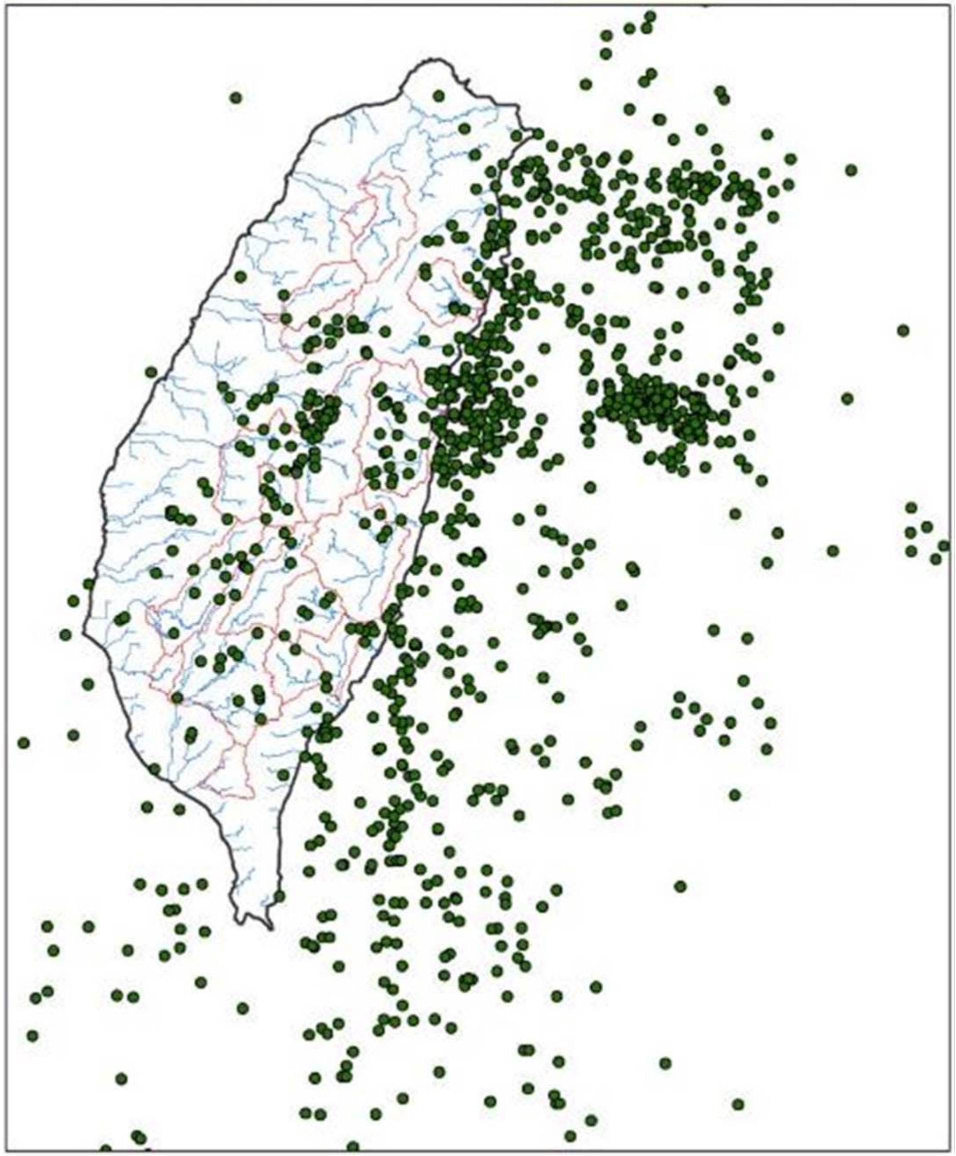
(Seed and Idriss, 1982)

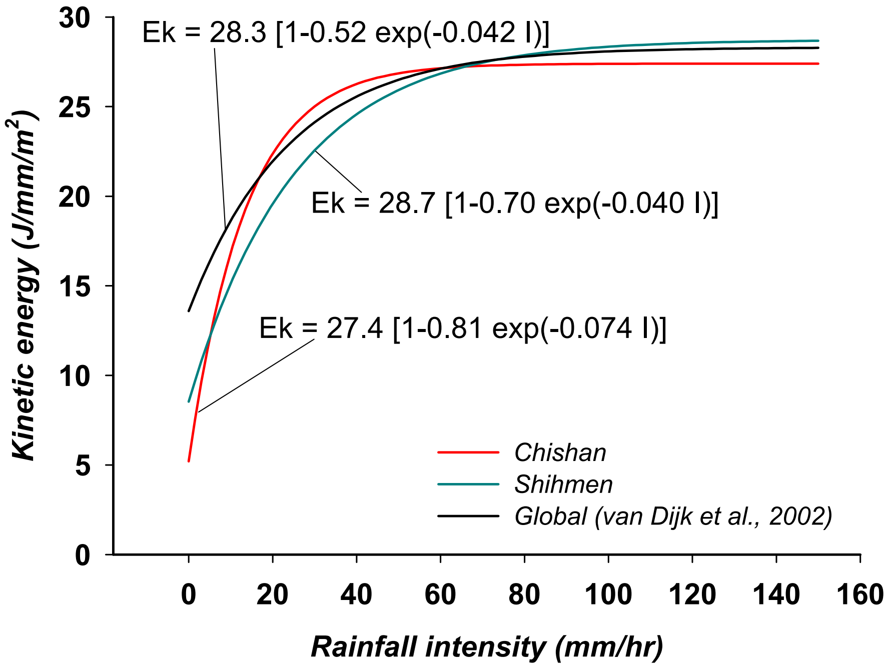


(Keefer, 1984)

Earthquake factor

- 1084 earthquakes during 1970-2009





$$m_i = \frac{4}{3}\pi D_i^3$$

$$v_i = 0.056D_i^3 - 0.912D_i^2 + 5.03D_i - 0.254$$

$$e_k = \frac{1}{2}\rho\sum_{i=1}^{20} n_i m_i v_i^2$$

m_i: volume of raindrop
D_i: diameter of raindrop
v_i: terminal velocity
e_k: rainfall kinetic energy
n_i: number of raindrop