Development of the landslide-integrated SWAT model

Presenter: Lu, Chih-Mei

Department of Bioenvironmental Systems Engineering,

National Taiwan University, Taiwan

國立臺灣大學 National Taiwan University

Outline

- Introduction
- Method
- Result and Discussion
- Conclusion and Future work

Introduction

Background

- Landslide has become an important sediment source in Taiwan due to the steep topography, geology, and natural disturbances (i.e. earthquakes, typhoons).
- The sediment contribution of landslide should be considered in the sediment transport simulation, and so on hydrologic model.

Objectives

- Integrate the landslide module in a hydrologic model (SWAT) to improve the sediment simulation performance.
- Calibrate landslide thresholds by total load observation.
- Evaluate the impact of landslide in watershed modeling.

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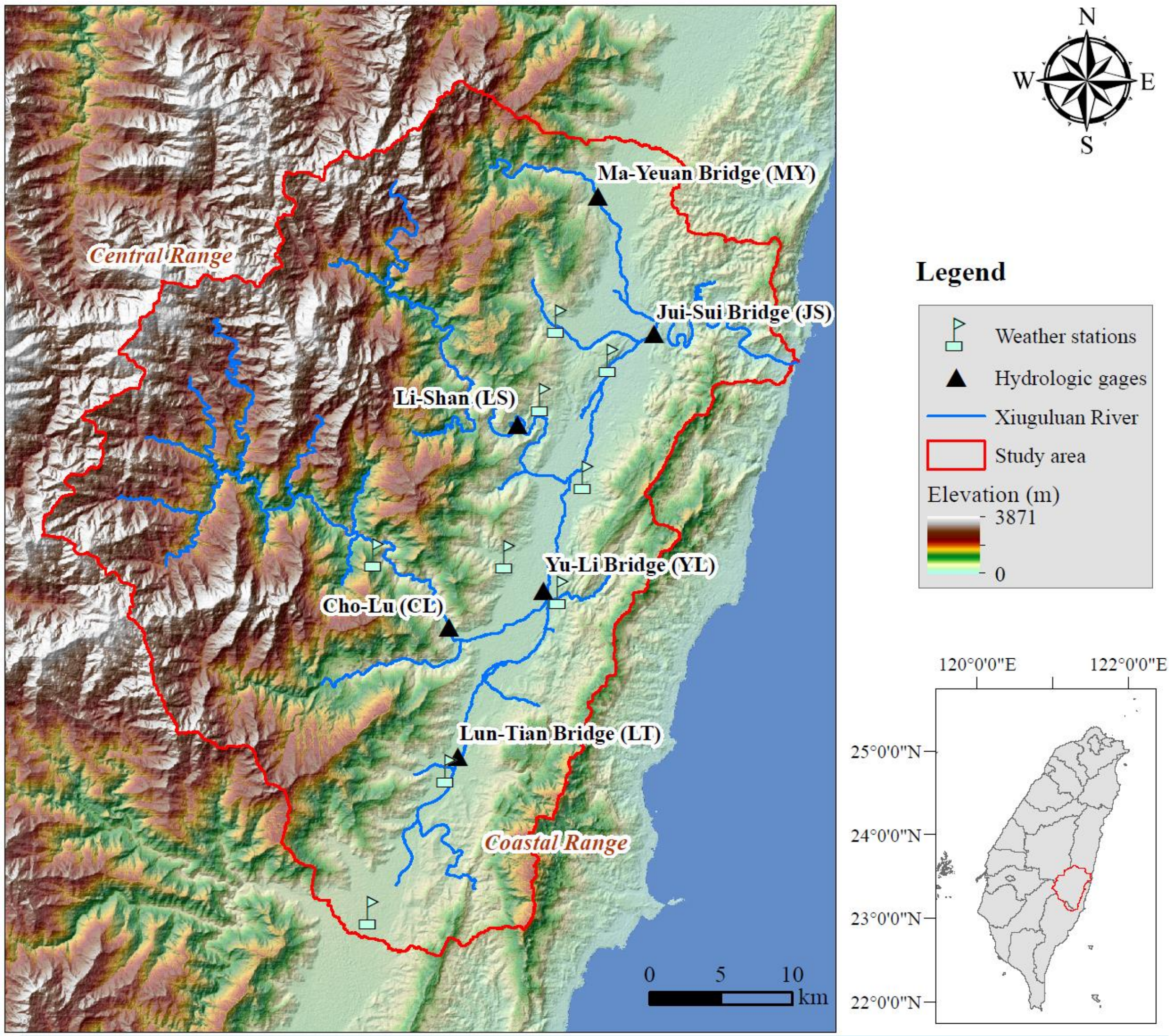
Introduction – Study area



Xiuguluan River Basin

- Area: 1,786.5 km^2
- Stream length: 104 km
- Highest elevation: 3,700 m
- Stream gradient: 1/34
- Average daily flow: 109 m^3/s

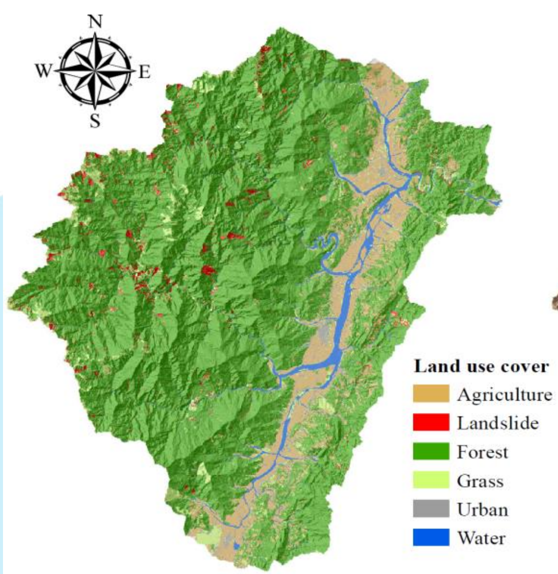
- Mean annual precipitation: 2,550 mm (69% of precipitation is concentrated in wet season (June to November))

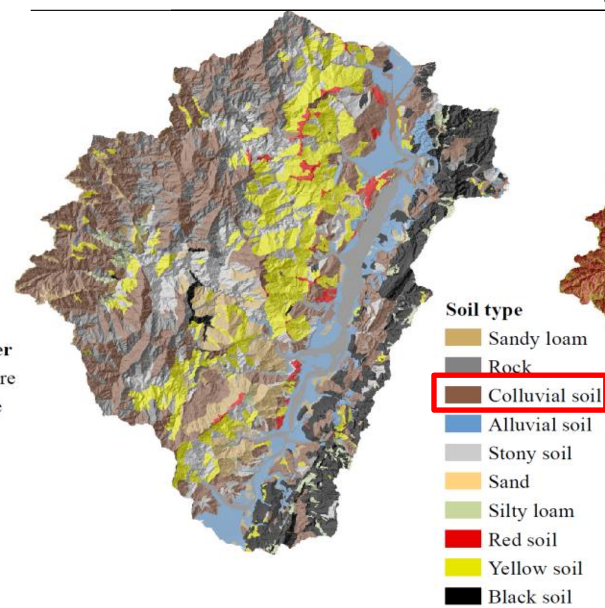
- The Central Range and Coastal Range are located at western and eastern side of basin, respectively

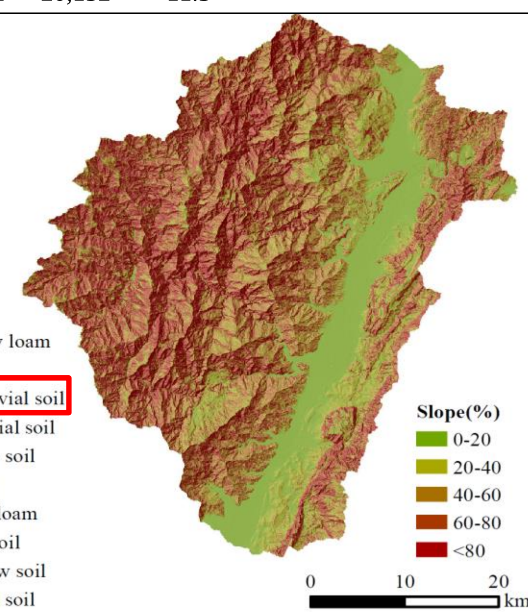
Introduction – Study area

- Major land uses: Forest and agriculture
- Landslide area was set by the historical landslide area map from 2004-2017.
- Landslide area is about 2.1%, most of them distributed at the headstream or along the upstream channel.
- Main soil type: colluvial soil (29.7%).

Land use cover	Area (ha)	Percentage (%)	Soil type	Area (ha)	Percentage (%)	Slope (%)	Area (ha)	Percentage (%)
Agricultural	18,983	10.6	Sandy loam	10,904	6.1	0-20	29,438	16.5
Landslide	3,832	2.1	Rock	26,744	15.0	20-40	22,770	12.8
Forest	138,634	77.6	Colluvial soil	52,977	29.7	40-60	36,408	20.4
Grass	8,796	4.9	Alluvial soil	13,774	7.7	60-80	39,539	22.1
Urban	2,811	1.6	Stony soil	21,853	12.2	<80	50,495	28.3
Water	5,594	3.1	Sand	33	0.0			
			Silt loam	2,999	1.7			
			Red soil	2,311	1.3			
			Yellow soil	26,904	15.1			
			Black soil	20,152	11.3			



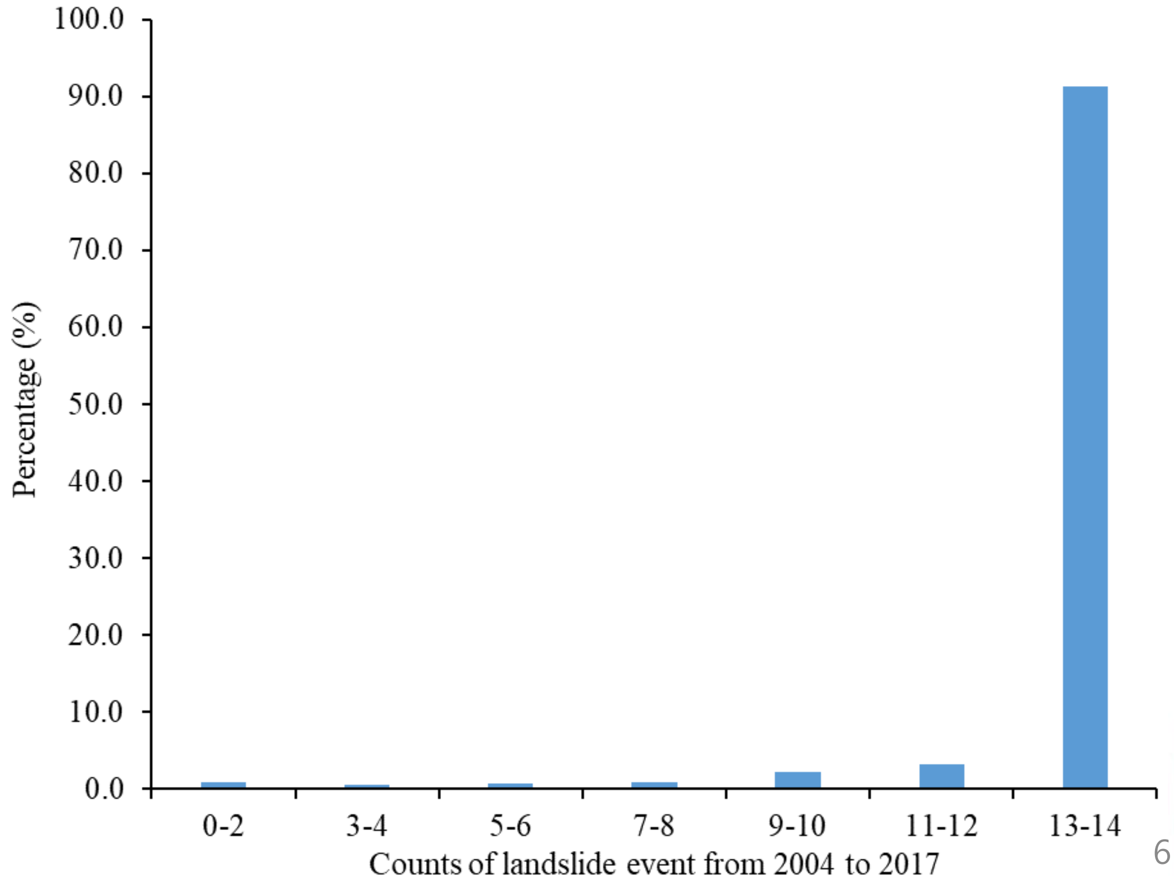




Introduction – Study area

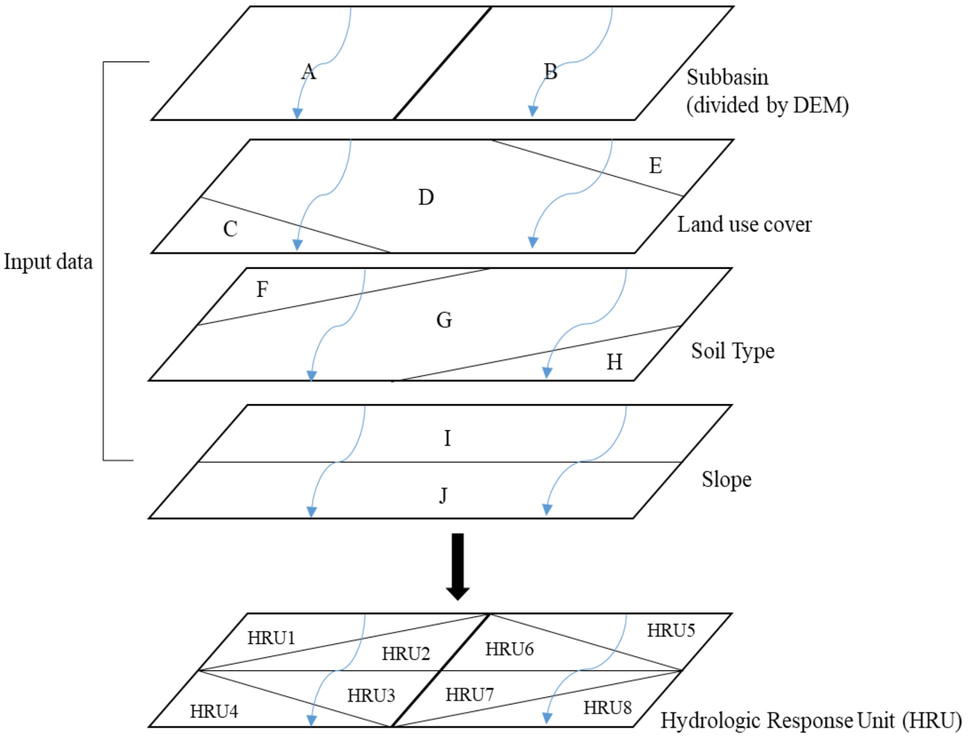
- Taiwan Forest Bureau had identified the landslide area in Taiwan by SPOT satellite every year from 2004 to 2017, the survey data had been set as the potential landslide area in this study.
- According to the historical landslide maps, 91.3% of landslide area re-occurred almost every year and a 96.9 % of landslide area last for more than 9 years.
- Therefore, these landslide area (3711.6 ha) was used as landslide reference for further analysis.

Landslide frequency		
Years of Landslide Occurred	Area (ha)	Percentage (%)
0-2	32.1	0.8
3-4	22.0	0.6
5-6	30.3	0.8
7-8	35.7	0.9
9-10	86.4	2.3
11-12	126.4	3.3
13-14	3498.8	91.3



Method – SWAT model

- Soil and Water Assessment Tool (SWAT model), developed by USDA-ARS in 1997, was used in this study.
- SWAT model can simulate water balance, sediment transport, nutrients, and pesticides at different special and temporal scales.
- The Hydrologic Response Unit (HRU) is the basic simulation unit in SWAT model.
- HRU of a subbasin is classified by land use cover, soil type and slope.



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Method – SWAT model

- The water cycle is simulated by water balance equation:

$$S_t = S_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right)_i$$

Where S_t is soil water content (mm); S_0 is initial water content (mm); R_{day} is the precipitation (mm); Q_{surf} is the surface runoff (mm); E_a is the evaporation (mm); w_{seep} is the seepage (mm); Q_{gw} is the baseflow (mm).

- The surface runoff is calculated by SCS Curve Number method:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a\right) + S}$$

Where I_a is the initial loss, included the surface storage, interception and infiltration; S is the retention parameter that calculated by Curve Number.

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Method – SWAT model

Soil loss

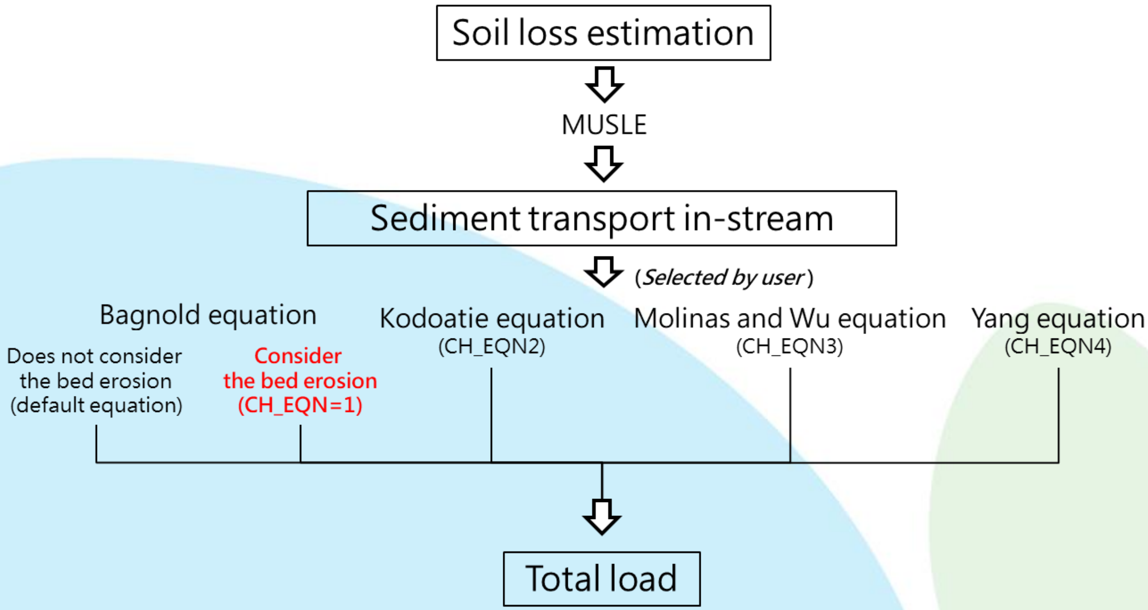
- SWAT model calculates the soil loss by Modified Universal Soil Loss Equation (MUSLE):

$$\mathrm{sed} = 11.8 \times (\mathrm{Q_{surf}} \times \mathrm{q} \times \mathrm{A})^{0.56} \times K \times C \times P \times LS \times CFRG$$

Where sed is soil loss (metric tons); Q_{surf} is the surface runoff (mm/ha); q is the peek runoff rate (m^3/s); A is the area of HRU (ha); K is the soil erodibility factor, C is cover and management factor, P is support practice factor, LS is topographic factor, CFRG is the coarse fragment factor.

Sediment transport

- 4 sediment transport equations to simulate the total load
- Among of them, Bagnold equation has two version that could choose to consider the bed erosion or not, in this study, we used the Bagnold equation with bed erosion to simulate the total load.



Method – SWAT model

- The sediment transport is limited by the transport capacity($conc_{ch,mx}$)

$$conc_{ch,mx} = spcon \cdot v_{ch,pk}{}^{spexp}$$

Where $conc_{ch,mx}$ is the maximum concentration of sediment that can be transported by the water (tons/m^3); spcon is linear coefficient; $v_{ch,pk}$ is the peak channel velocity (m/s); spexp is the exponent coefficient.

Deposition

- While the initial sediment concentration in-stream is more than transport capacity, the deposition will be the dominant process in the reach segment.

$$sed_{dep} = (conc_{sed,ch} - conc_{ch,mx}) \cdot V_{ch}$$

Where sed_{dep} is the amount of sediment deposited in the reach segment (metric tons); $conc_{sed,ch,i}$ is the initial sediment concentration in the reach; V_{ch} is the volume of water in the reach segment (m^3).

Degradation

- On the contrary, while the $conc_{sed,ch} < conc_{ch,mx}$, degradation will be the dominant process in the reach segment.

$$sed_{deg} = (conc_{ch,mx} - conc_{sed,ch}) \cdot V_{ch} \cdot K_{ch} \cdot C_{ch}$$

Where sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons); K_{ch} is the channel erodibility factor; C_{ch} is the channel cover factor.

Method – Revision of Soil Loss

- We revised the soil loss module by integrated the landslide module in the soil loss module.
- The landslide module includes two parts: landslide thresholds and landslide volume estimation.
- Thresholds of landslide occurrence: Daily precipitation and fraction of soil water content.
- Revised Khazai and Sitar depth-area equation from Taiwan Soil and Water Conservation Hand Book is used to estimated the landslide volume.
- The landslide module will run if the daily precipitation and fraction of soil water content exceed the thresholds.

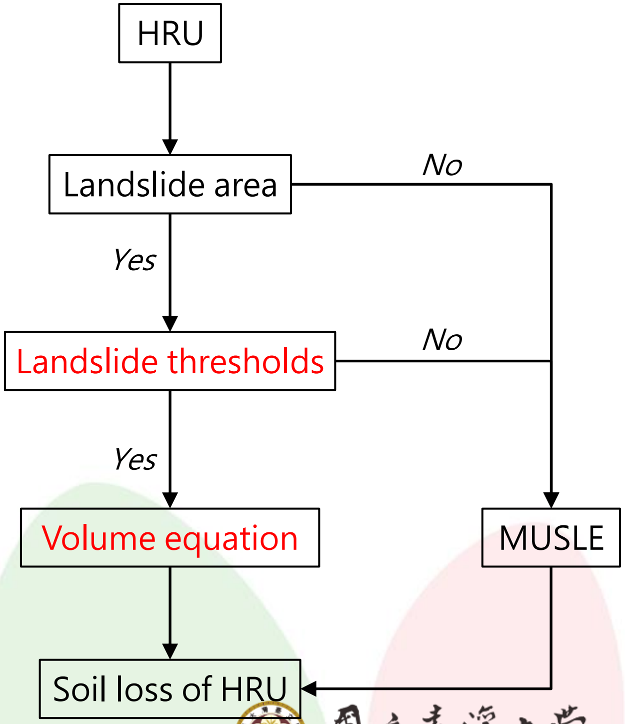
Landslide thresholds

- Fraction of soil water content is calculated by following.

$$SWFR = \frac{SW_{sim}}{AWC}$$

Where $SWFR$ is fraction of soil water content; SW_{sim} is simulated soil water content (mm); AWC is the maximum of soil water content (mm), which is defined in database.

- These thresholds as the parameters are calibrated with total load.



Method – Landslide module

Landslide volume estimation

- The revised Khazai and Sitar equation consists of two parts: depths of landslide area and volume correction equation:
  - The depth of landslide area is classified by slope (Khazai and Sitar, 2000):

$$\begin{cases} slope < 30^\circ, depths = 2.0\ m \\ 30^\circ < slope < 40^\circ, depths = 1.5\ m \\ slope > 40^\circ, depths = 1.0\ m \end{cases}$$

  - The volume correction equation (Chuang and Lin, 2010):

$$V_L = 5.792 V_{LK} - 45366$$

where V_L is landslide volume (m^3) , V_{LK} is the landslide volume calculated by Khazai and Sitar method.

Method – Model Uncertainty

- The SWAT Calibration Uncertainty Program (SWAT-CUP) was used to analysis the model uncertainty in this study, we calibrated the parameters which p-value is less or near 0.05.
- The SWAT-CUP calibrates the parameters in SWAT model through several methods (SUFI2, ParaSol, GLUE, MCMC, and PSO).
- The SUFI2 (Sequential Uncertainty Fitting version 2), which is the most efficient method (Abbaspour et al., 2012) is applied in this study.
- Model performance criteria: R^2 , NSE (Nash-Sutliffe Efficiency), and PBIAS (Percent Bias) (Moriasi et al., 2015).
- The model performance suggested by Moriasi et al. (2015) have different standards for different simulation objects. For example, it is satisfactory for daily streamflow when $R^2 > 0.5$, but for monthly sediment, the model is satisfactory when $R^2 > 0.45$.

Model performance for daily streamflow and monthly sediment (Moriasi et al., 2015)

Model performance	Daily Streamflow			Monthly Sediment Simulation		
	R^2	NSE	PBIAS(%)	R^2	NSE	PBIAS(%)
Very good	$R^2>0.85$	NSE>0.80	|PBIAS|≦10	$R^2>0.80$	NSE>0.80	|PBIAS|≦1
Good	$0.70≦R^2≦0.85$	0.70≦NSE≦0.80	10<|PBIAS|<15	$0.65≦R^2≦0.80$	0.70≦NSE≦0.80	1<|PBIAS|<10
Satisfactory	$0.50<R^2<0.70$	0.50<NSE<0.70	15≦|PBIAS|≦45	$0.40<R^2<0.65$	0.45<NSE<0.70	10≦|PBIAS|≦20
Not satisfactory	$R^2≦0.5$	NSE≦0.5	|PBIAS|≧45	$R^2≦0.4$	NSE≦0.45	|PBIAS|≧20

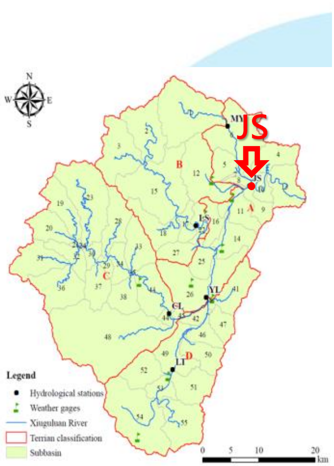
Result and Discussion
- Streamflow(Represented by JS)

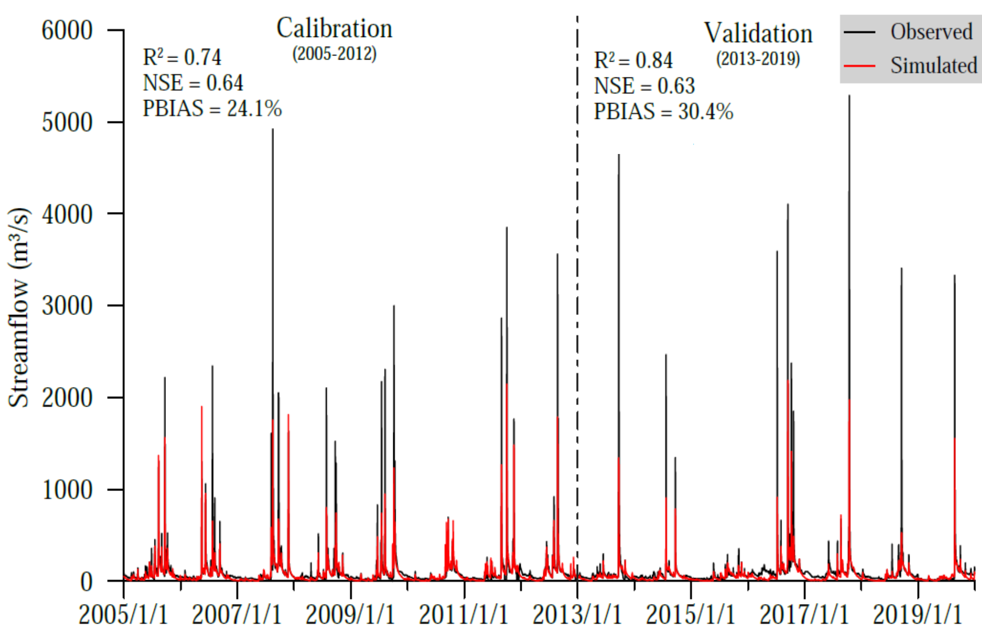
- After the sensitivity analysis, 8 flow-related parameters were calibrated and validated through the land use type and the subbasin group classified by topography, the group A and D represent the Coastal Range region, group B and C is for Central Range region.

- Two calibration methods was use in streamflow calibration: **Relative** (default value multiply by (1+given value)) and **Replace** (replace by given value).

- The calibration and validation showed the performance of streamflow simulation of SWAT model is "Satisfactory" to "Good" (R^2 >0.7, NSE > 0.5, |PBIAS|<45%), can generally simulate the characteristics of Xiuguluan River Basin.

- The model underestimated the peak flow, but simulated well during low-flow periods.



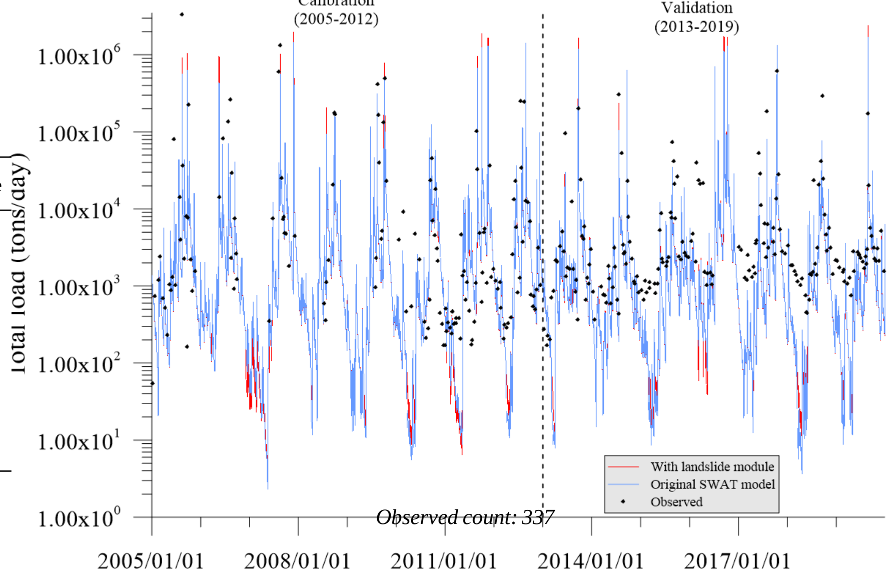


Parameter	Unit	Method	Class	Calibrated range	Fitted value
CN2	-	Relative	Agriculture	-0.55 ~ -0.30	-0.32
			Forest and grass	-0.30 ~ 0.05	-0.03
CH_N2	-	Replace	All	0.04 ~ 0.06	0.05
CANMX	mm	Replace	Forest	20 ~ 90	29.57
GW_REVAP	mm	Replace	B	0.03 ~ 0.07	0.06
			C	0.02 ~ 0.04	0.04
			D	0.03 ~ 0.07	0.02
GWQMN	mm	Replace	B	30 ~ 100	71
			C	30 ~ 100	37
			D	150 ~ 250	229
GW_DELAY	days	Replace	A	1.0 ~ 5.0	4.1
			B	0.1 ~ 1.0	0.6
			C	2 ~ 10	3.5
			D	1 ~ 10	9.7
REVAPMN	mm	Replace	A	400 ~ 800	751
			B	1000 ~ 1500	1450
SOL_AWC	mm	Relative	A and D	-0.6 ~ 0.4	-0.5
			B	-0.5 ~ -0.2	-0.49
			C	-0.15 ~ 0.00	0.13

Result and Discussion -Total Load(Represented by JS)

- Few study simulated the daily sediment (i.e., sediment concentration, total load), therefore, monthly total loads was simulated in this study.
- A total of 6 sediment-related parameters and 2 thresholds have been calibrated and validated.
- The fitted thresholds values: daily precipitation (168 mm) and fraction of soil water content (0.65).
- Model performance: "good" to "very good" model performance for R^2 (R^2 > 0.65 and 0.8); "not satisfactory" for NSE and PBIAS (NSE <0.45, |PBIAS|>45%) during calibration and validation periods.
- Compared with the original SWAT model, the landslide module increased the total loads at the peak sediment event during whole simulation period (2005-2019), which improved the model performance during calibration period.
- However, due to the lack of the observation of total loads the positive effect of landslide module integration did not significant on improving model performance .

Parameter	Unit	Method	Class	Calibrated range	Fitted value
SPCON	-	Relative	-	0.1 ~ 0.35	0.27
ADJ_PKR	-	Replace	-	1.5 ~ 2.0	1.89
PRF_BSN	-	Replace	-	1.5 ~ 2.0	1.9
SPEXP	-	Replace	-	1.5 ~ 2.0	1.88
CH_COV2	-	Replace	-	1.0 ~ 2.0	1.67
CH_ERODMO	-	Replace	-	0.4 ~ 1.0	0.56
Precipitation (landslide thresholds)	mm	Replace	-	150 ~ 200	**168**
Fraction of soil water content (landslide thresholds)	-	Replace	-	0.60 ~ 0.70	**0.65**

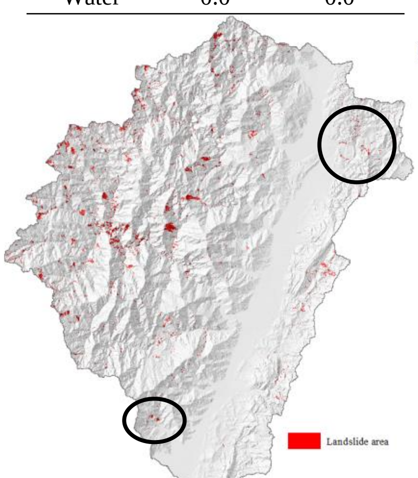


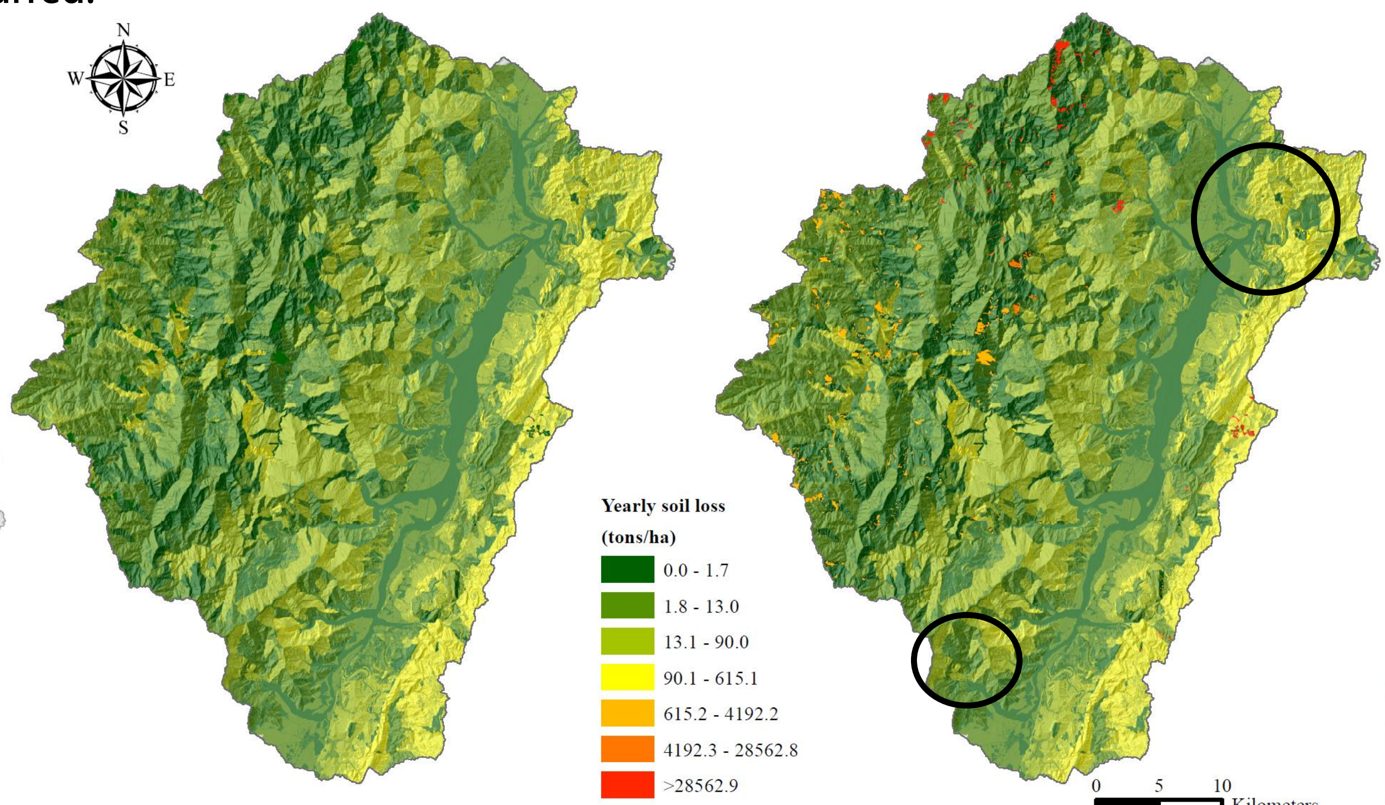
Period	Parameter	Landslide module	Original SWAT
Cal.	R^2	0.84	0.85
	NSE	0.36	0.23
	PBIAS (%)	80.44	84.27
Val.	R^2	0.71	0.70
	NSE	0.11	0.11
	PBIAS (%)	82.39	82.28

Result and Discussion - Soil Loss(HRU level)

- The soil loss of landslide area had significantly increased after integrated the landslide module.
- The average soil loss from landslide area is increased to 146.8 - 15,972.0 tons/ha per year.
- Instead of landslide area, others area represented the same result of soil loss simulation.
- Not all of landslide area is triggered by landslide module, showing the thresholds can control where the landslide event occurred.

Land use	Soil loss (tons/ha/year) Original SWAT	Landslide module
Agriculture	23.2	23.2
Landslide	**146.8**	**15972.0**
Forest	26.0	26.0
Grass	24.0	24.0
Urban	2.7	2.7
Water	0.0	0.0

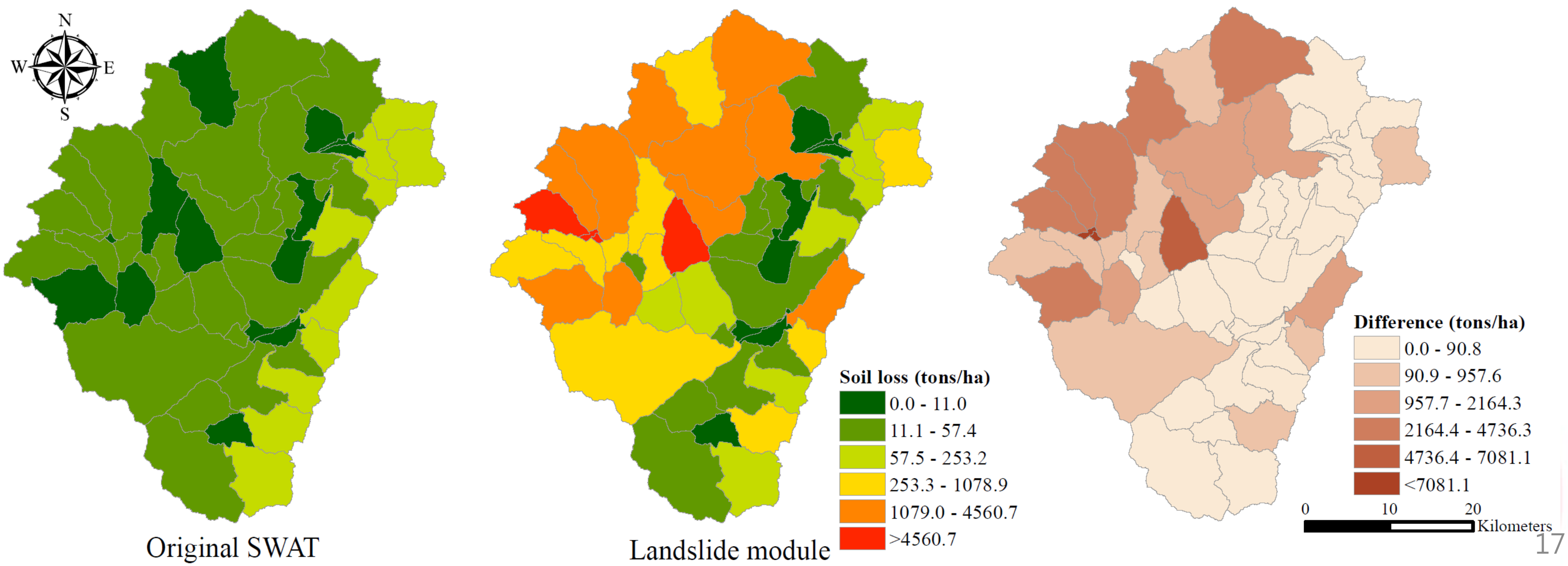




Original SWAT model With landslide module

Result and Discussion - Soil Loss(subbasin level)

- The huge difference of soil loss simulation was shown at the subbasin level.
- The original SWAT model considers less soil loss in the Xiuguluan River Basin(0 to 253.2 tons/ha).
- With the landslide module, the soil loss significantly increased (90.9 to 19,232.6 tons/ha).
- The slope distribution of the Xiuguluan River Basin resulted in landslide at western area, and thus increased more soil loss through the landslide module.
- The soil loss at the subbasin showed the soil loss caused by landslide acted an important role in hydrological simulation.



Conclusion

- SWAT model can generally simulate the streamflow characteristics of the Xiuguluan River Basin, but underestimated the peak flow.
- The calibrated landslide thresholds indicated that the landslide event might occur while daily precipitation is more then 168 mm with fraction of soil water content greater than 0.65.
- The total load simulation result indicated that both models can simulate the trend of daily total load.
- Landslide module can slightly improve the model performance with the consideration of the impact of landslide event.
- The simulation of soil loss indicated that the soil loss from landslide area is an important sediment source, thus landslide-related watershed is suggested to considering the impact of landslide area when modeling.
- Only 337 observation data of total loads during the simulation period (15 years). If there have been more reference points, the simulation would be more accurate and reasonable.
- Since different landslide volume equations might result in different simulation result, other sediment transport equations will be test in the future .

Thanks for listening!
Question?

Contact email: d10622003@ntu.edu.tw