Estimation of Residual Slope Instability and Associated Unstable Sediment Transport Impacts

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In recent years, the increasing frequency of extreme rainfall and seismic events has intensified the generation and remobilization of unstable sediment within watersheds, posing significant threats to downstream villages and infrastructure. This study develops an integrated modeling framework for simulating unstable sediment transport and impact assessment in selected high-risk catchments in Taiwan. The proposed approach integrates remote sensing observations and numerical simulations, utilizing the RAMMS model to assess sediment transport impacts. A block-release numerical boundary condition setup is adopted to represent sediment supply from slope failures, while channel processes such as bed erosion, entrainment, and multi-stage sediment transport are explicitly considered. Model calibration and validation are conducted using multiple rainfall scenarios, ranging from moderate to extreme events, enabling the establishment of relationships between erosion rate parameters and rainfall intensity. In addition, multi-temporal optical imagery and InSAR techniques are employed to quantify both long-term and short-term sequential behaviors of unstable slopes, providing critical constraints on sediment source dynamics. The results indicate that extreme rainfall scenarios substantially increase flow depth and impact extent, thereby posing significant threats to the safety of downstream infrastructure. The proposed framework offers practical applications for hazard zonation, early warning threshold development, and adaptive watershed management, contributing to advancing soil and water conservation and hydraulic engineering practices.

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Outline

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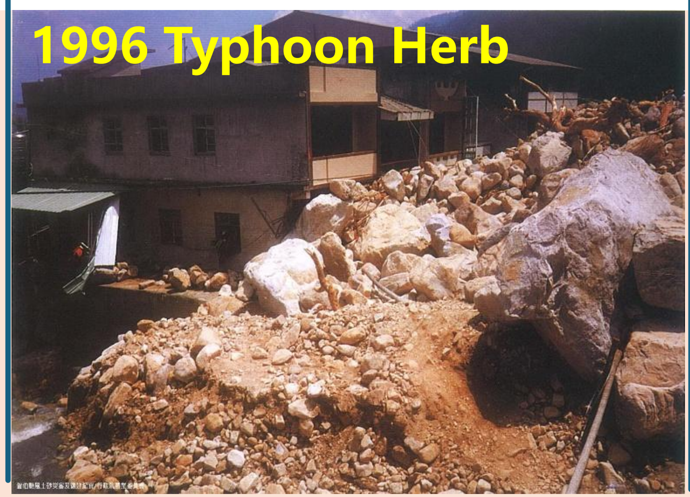
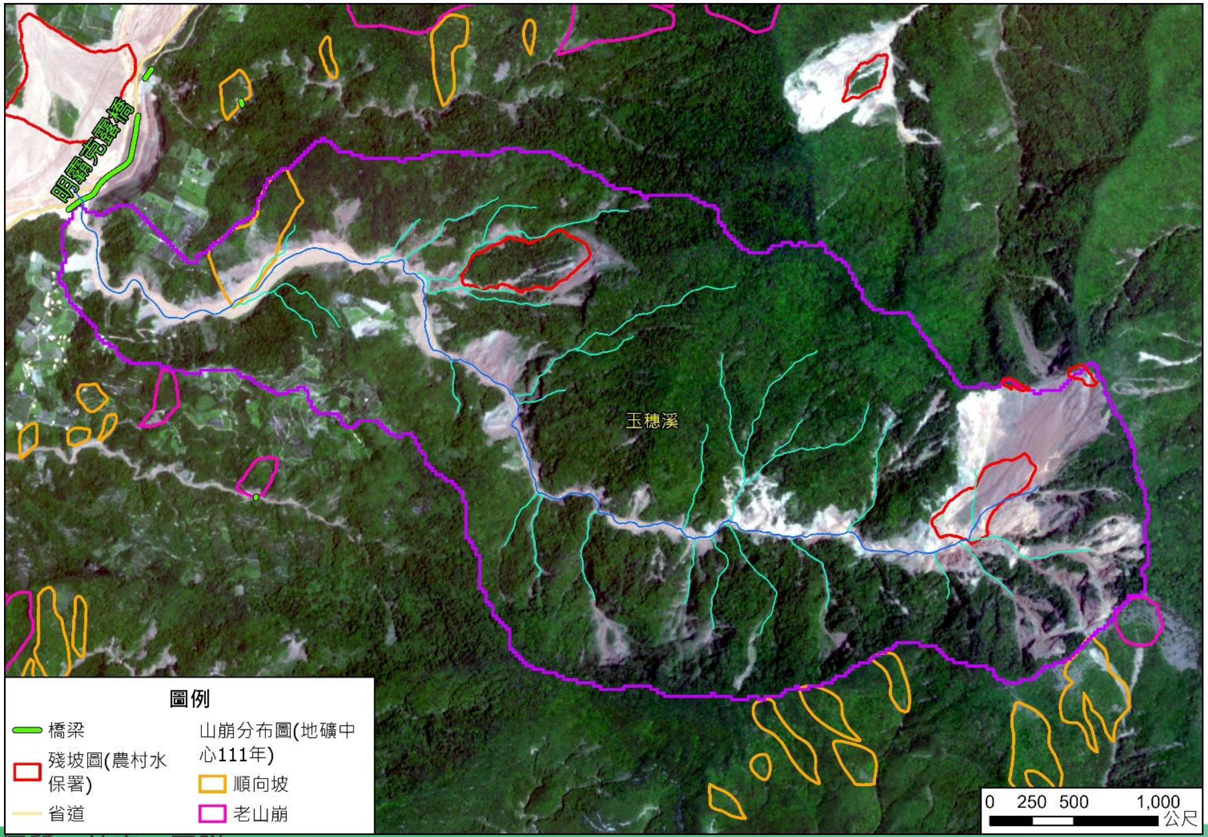
- Runout Potential of Unstable Sediment
- Runout Impact of Unstable Sediment
- Conclusions

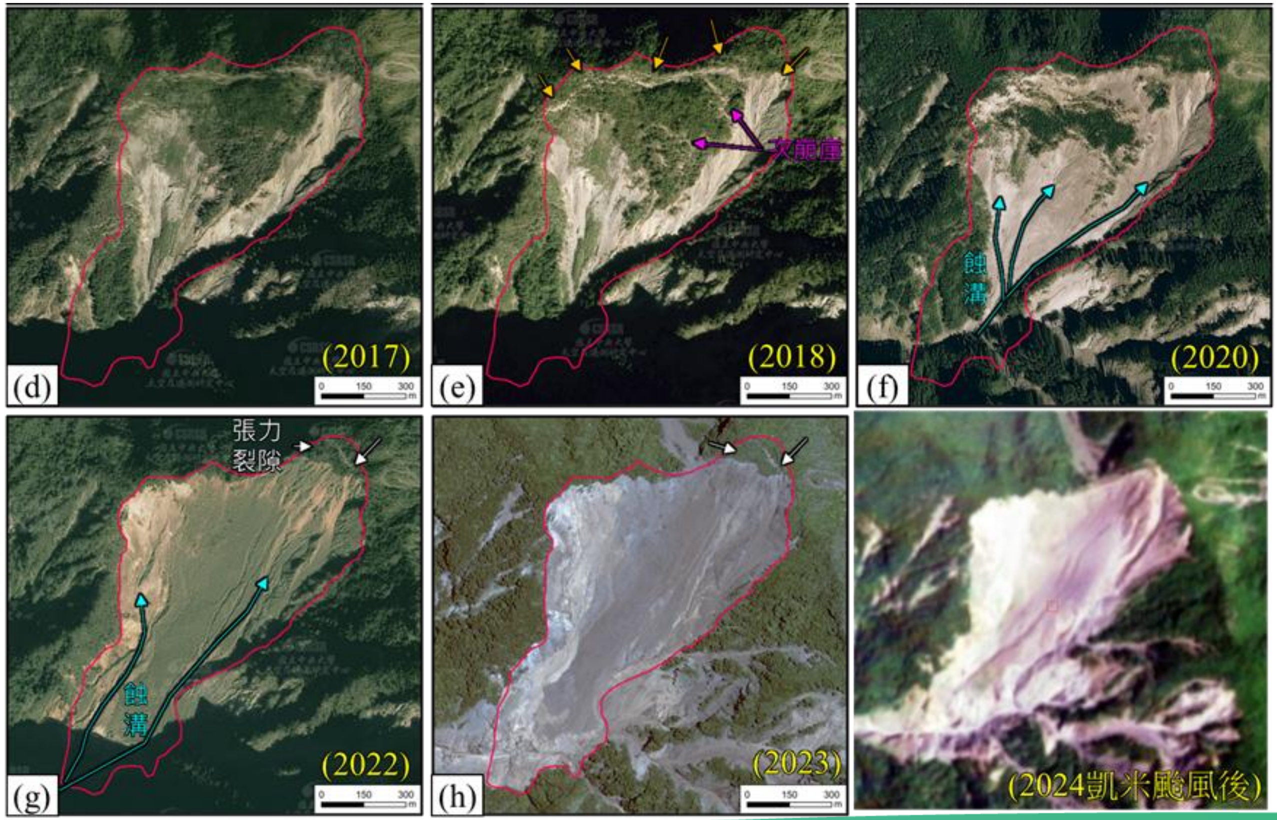
Introduction

Type	Debris Flow	Large-scale Landslide	Unstable Sediment
Event	**1996 Typhoon Herb** devastated the Central Cross-Island Highway	**2009 Typhoon Morakot** caused catastrophic damaged to Southern Taiwan	**2021 Typhoon Lupit** unstable sediment runout destroy the MingbaKelu Bridge
Definition	**Debris Flow:** A gravity driven mixture of sediment and water.	**Large-sacle Landslide:** Area>10 ha、 Volume>10^5 m^3、 Depth>10 m。	**Unstable sediment:** Massive amounts of sediment can be triggered by rainfall or earthquakes, causing severe downslope sediment disasters.
Protection	Households	Households	At-risk Road and Bridges
Disasters			

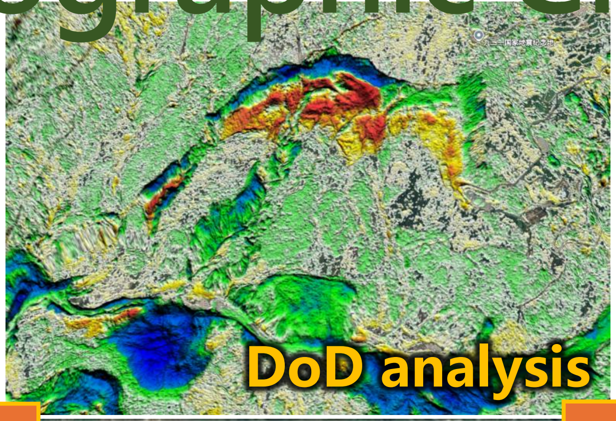
Residual Slopes and Unstable Sediment

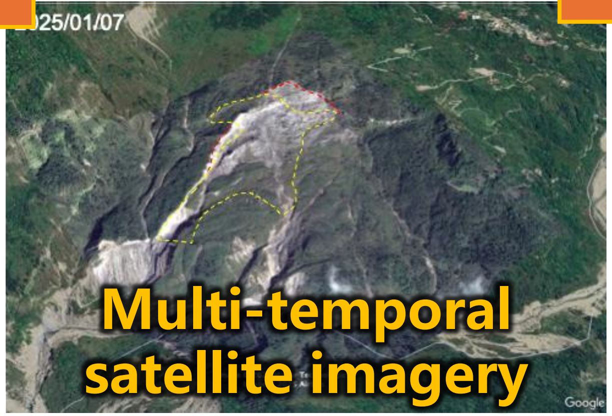
- The dynamic of residual slopes and unstable sediment in river channels under conditions of temporal equilibrium or instability within a watershed.
- The increasing frequency of extreme rainfall and seismic events has intensified the generation and remobilization of residual slope and sediment-related disasters.

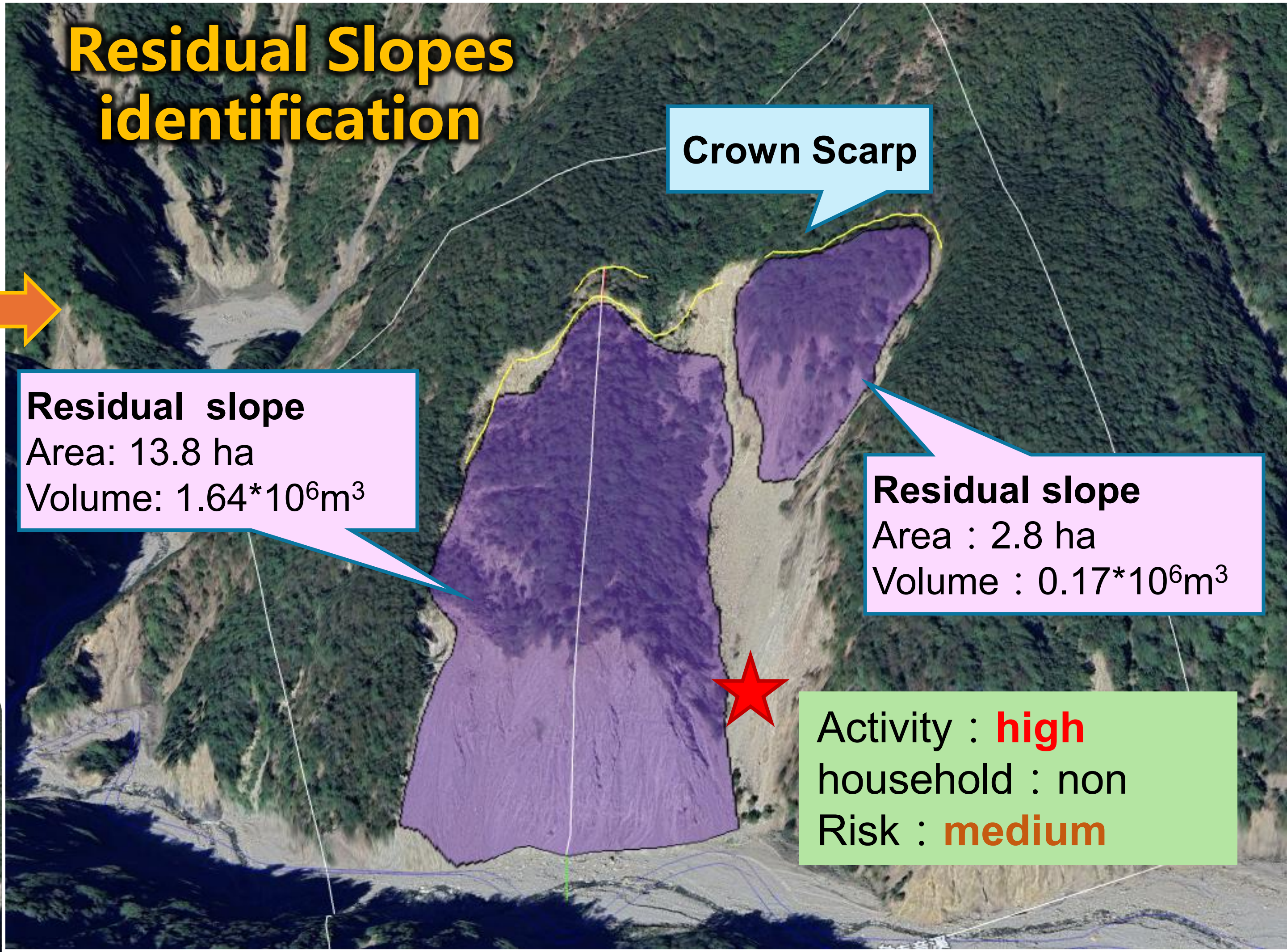




Topographic Characteristics Screening







Laonong River, GaoPing Watershed

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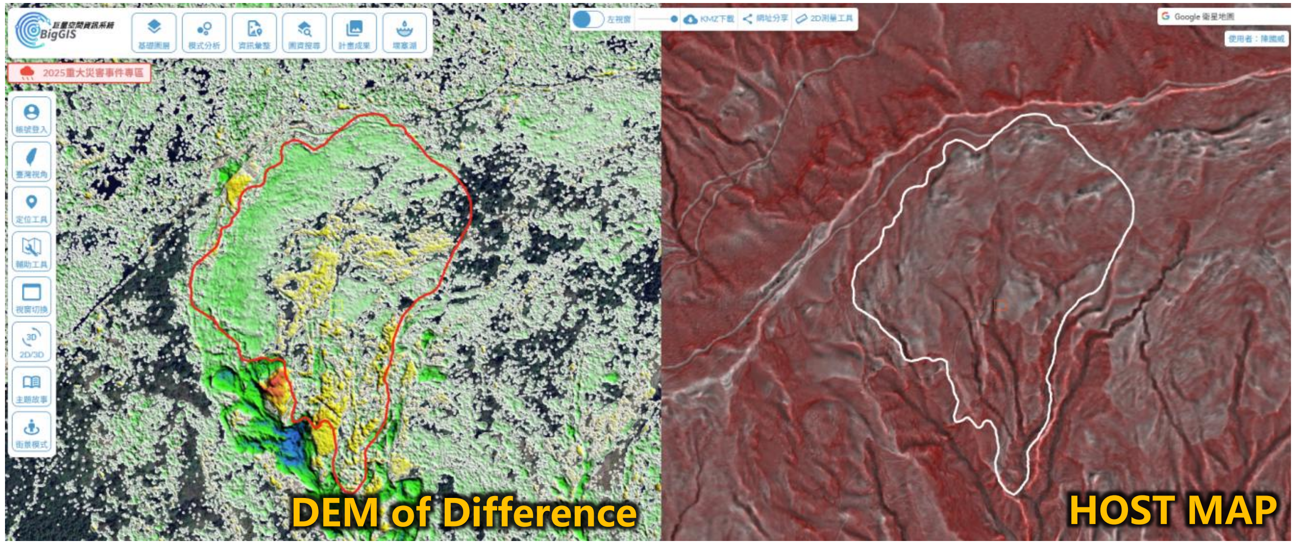
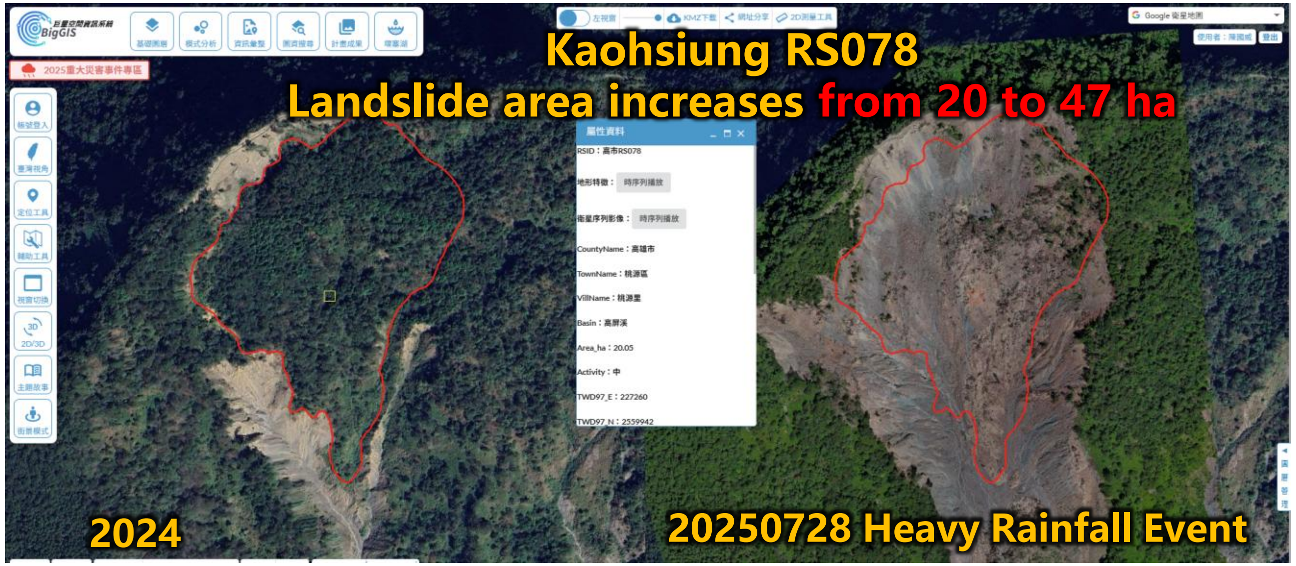
Identification of Residual Slope

A total of 552 Residual Slopes were identified through the Integration of high-resolution DEM differencing, HOST MAP, and multi-temporal satellite imagery.





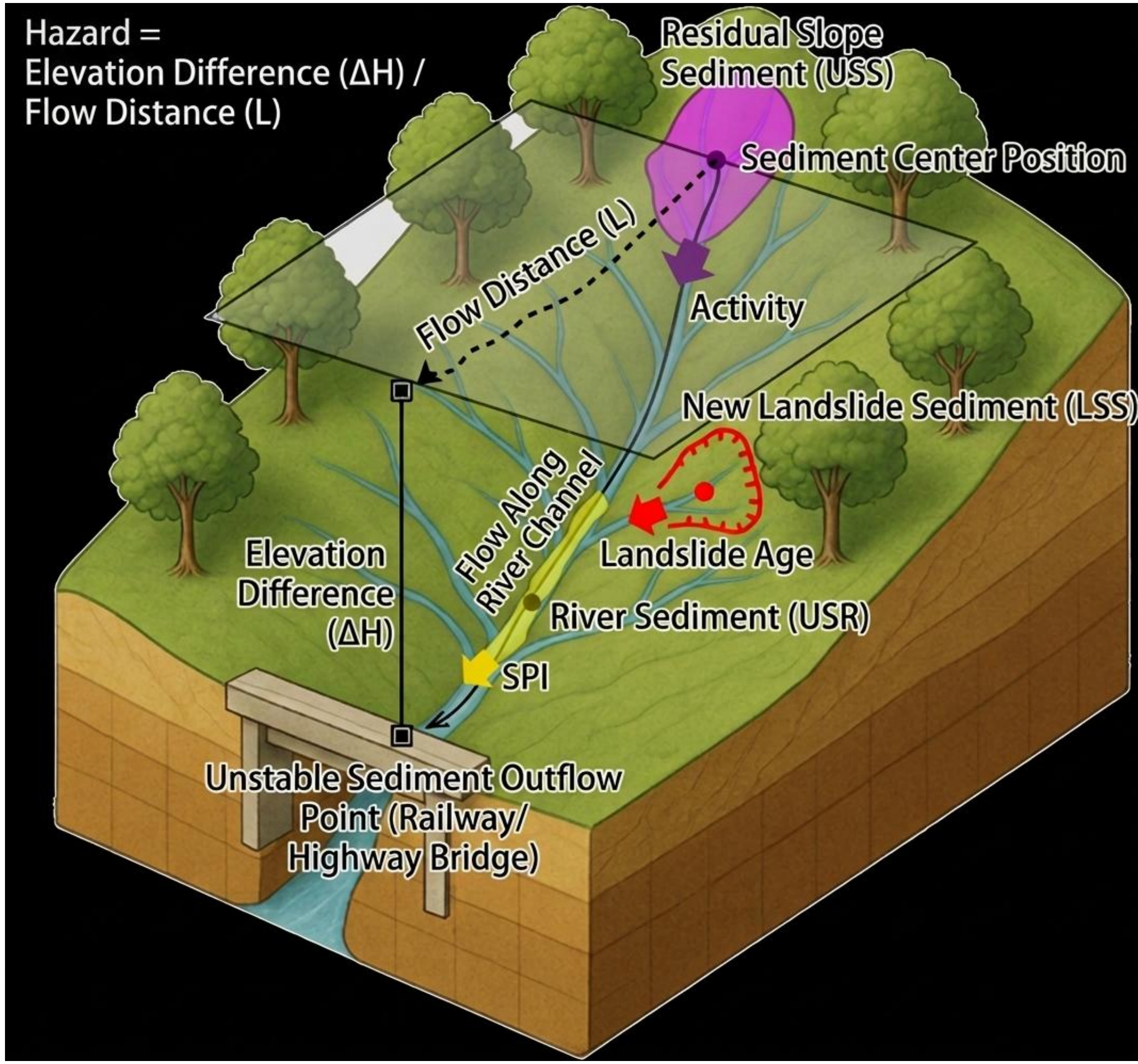
Runout Potential of Unstable Sediment

Sediment runout potential of Residual slope and channel and landslide (P_{total}) and it's susceptible：

$$P_{total} = P_{USS} + P_{USR} + P_{LSS}$$

$$\text{Susceptible} = Ln(P_{total} / Area)$$

1. **Residual Sed.** (P_{USS}) = Volume × Activity × $Hazard_1$
2. **Channel Sed.** (P_{USR}) = Volume × USP × $Hazard_2$
3. **New landslide** (P_{LSS}) = Volume × Age× $Hazard_3$

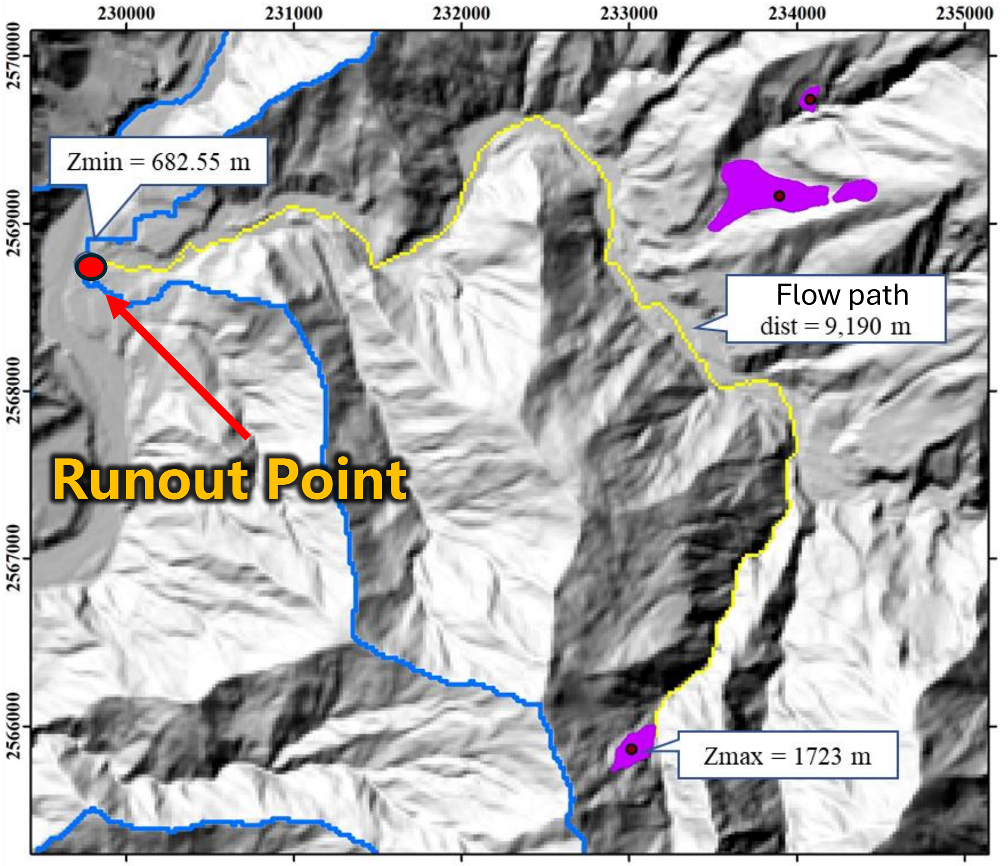


Runout Potential of Unstable Sediment

Runout Potential of unstable sediment on residual slopes (P_{USS})：

- **Volume of unstable sediment on residual slopes** (V_s) ：
  - volume-area empirical Eq. $V_L = 0.1025 \times A_L^{1.401}$
- **Weight of activity** (W_{act}) ：
  - DoD analysis; multi-temporal satellite imagery
  - Activity level: High(0.9)、Medium(0.4)、Low(0.2)
- **Hazard** (H_{d1})：
  - elevation deviation / flow path distance

$$P_{USS} = \sum_{1}^{n} V_s \times W_{act} \times H_{d1}$$



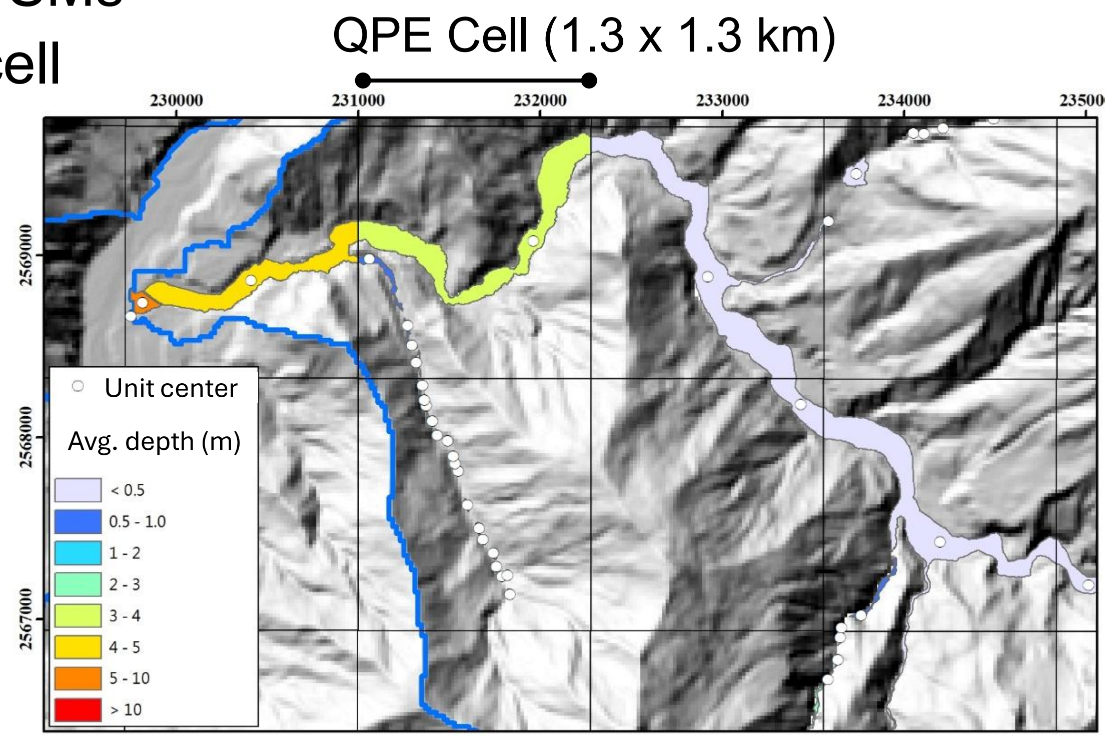
Residual slope unstable sediment: elevation difference and flow distance

Runout Potential of Unstable Sediment

Runout Potential of unstable sediment in channel (P_{USR}) :

- **Volume of unstable sediment in channels** (V_r) :
  - Volume estimation via satellite imagery and DSMs (Img2dod) based on QPE (1.3 km ×1.3 km) cell
- **Weight of Unit Stream Power** (W_{SPI}) :
  - Unit stream power within each cell
- **Hazard** (H_{d2}) :
  - elevation deviation / flow path distance

$$P_{USR} = \sum_{1}^{n} V_r \times W_{SPI} \times H_{d2}$$



Sediment volume and QPE Cell

Runout Potential of Unstable Sediment

Runout Potential of New landslide sediment (P_{LSS}) :

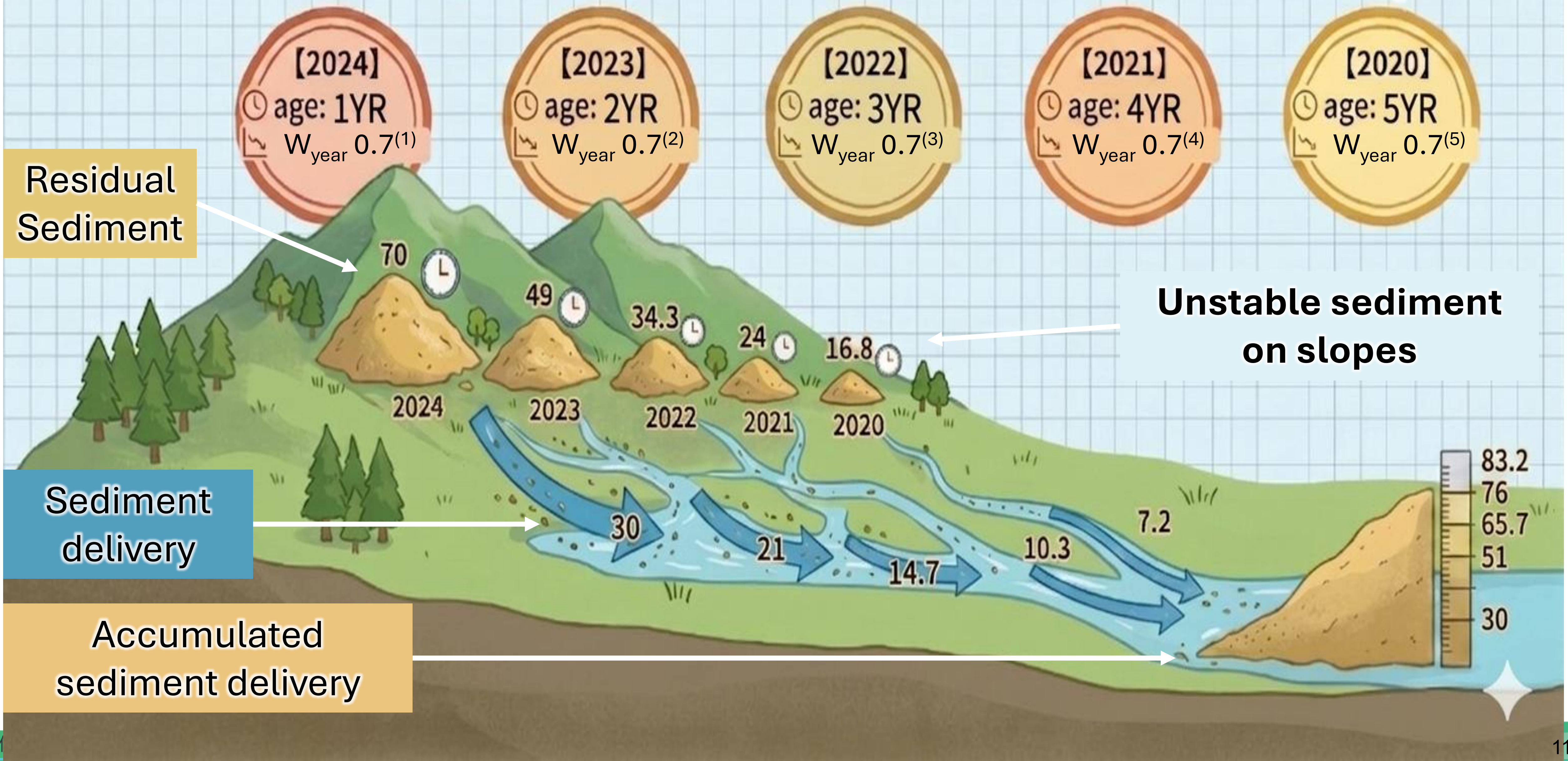
$$P_{LSS} = \sum_{1}^{n} V_L \times W_{year} \times H_{d3}$$

- **Volume of Newborn landslide on slopes** (V_L) :
  - landslide catalog **within 5 years** (**area ≥ 2 ha**)
  - volume-area empirical Eq. $V_L = 0.1025 \times A_L^{1.401}$
- **Weight of the event age** (W_{year}) :
  - A **reduction factor of 0.7** is applied,
  - the values calculated based on 0.7^n
  - n is **the slump age** (years ago before baseline 2025)
- **Hazard** (H_{d3}) :
  - elevation deviation / flow path distance

Landslide catalog	Number of years	Reduction coefficient	Residual sediment	Sediment delivery	Accumulated Sediment delivery
2024	1 year	$0.7^{(1)}$	70	**30**	30
2023	2 year	$0.7^{(2)}$	49	**21**	51
2022	3 year	$0.7^{(3)}$	34.3	**14.7**	65.7
2021	4 year	$0.7^{(4)}$	24	**10.3**	76
2020	5 year	$0.7^{(5)}$	16.8	**7.2**	83.2

Example: Initial mass 100 (m^3)

Volume of New landslide sediment on slopes



Runout Potential of Unstable Sediment

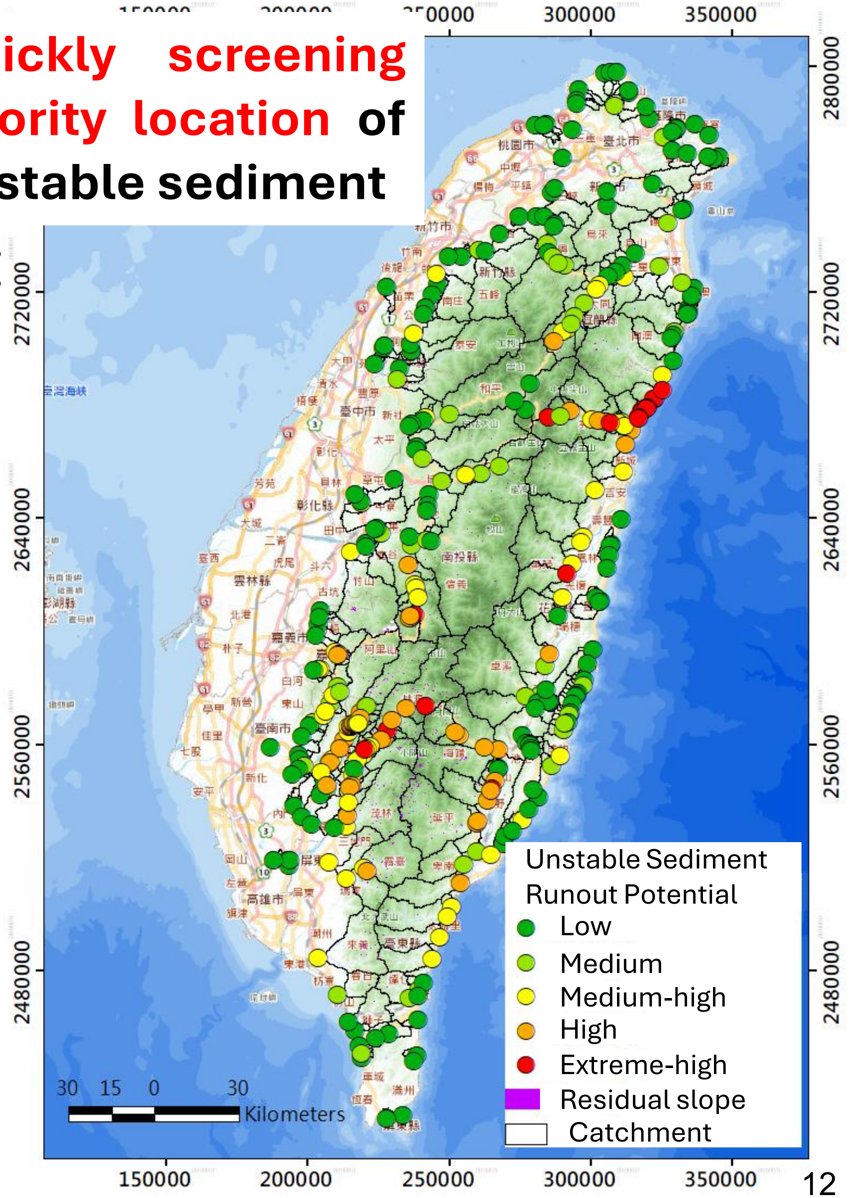
Total runout potential of Residual slope and channel and new landslide (P_{total}) and susceptible：

$$P_{total} = P_{USS} + P_{USR} + P_{LSS}$$

$$\text{Susceptible} = Ln(P_{total} / Area)$$

Potential Level	P Value	Class	Number	
			Site	%
Low	0.0 ~ 0.9	1	162	50.1
Medium	1.0 ~ 2.4	2	39	12.1
Medium-high	2.4 ~ 3.6	3	59	18.3
High	3.6 ~ 5.5	4	45	13.9
Extreme-high	≥5.5	5	18	5.6
Total			323	100%

Quickly screening priority location of unstable sediment



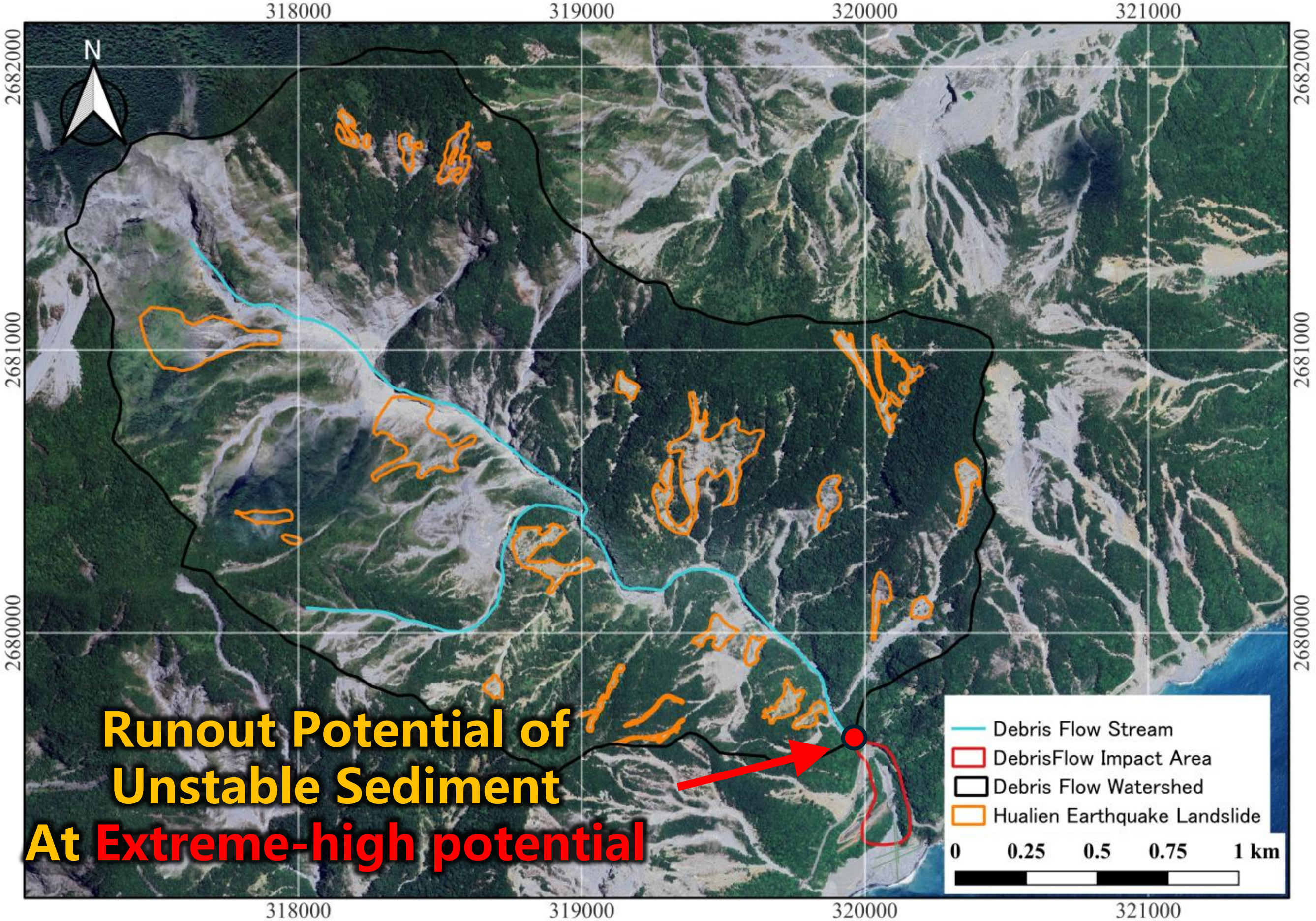
Unstable Sediment Disasters

Unstable Sediment Disasters

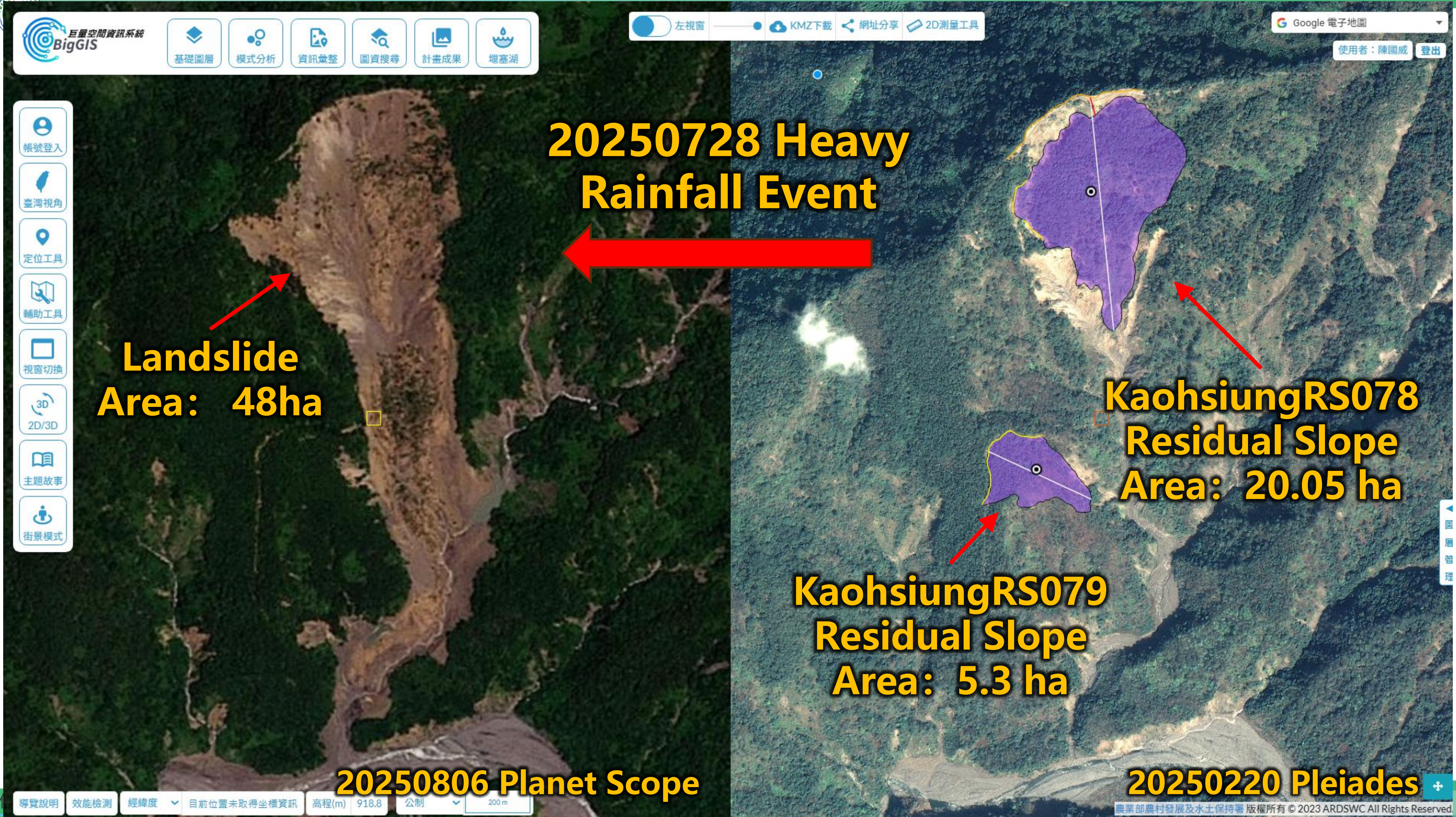
Hsiulin district, Hualien County

25 New Landslides

New Landslide Area and Ratio: 31.7 ha; 6%



Debris flow surge onto the railway


20250728 Heavy Rainfall Event
Landslide
Area: 48ha
KaohsiungRS078
Residual Slope
Area: 20.05 ha
KaohsiungRS079
Residual Slope
Area: 5.3 ha
20250806 Planet Scope
20250220 Pleiades
巨量空間資訊系統 BigGIS
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Impact of Unstable sediment runout simulation

Estimating the runout impact of unstable sediment under different rainfall conditions using RAMMS

Catchment Numerical Numerical Simulation

Rainfall conditions

200mm
350mm
500mm
650mm
900mm

Climate Change
e.g., 200-year Return Period rainfall + 200-year Return Period one-day storm rainfall change rate (%)

Unstable Sediment Volume

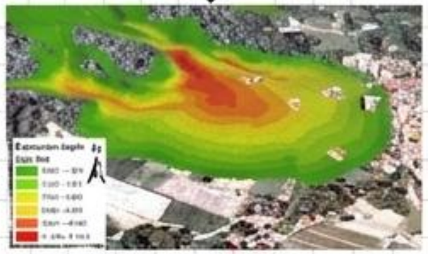
Simulation Parameter Assessment

Unstable Sediment Volume and Rainfall Reduction Relationship

Unstabie Sadiment Volume (m³)	Ramlali Retum Petiod (Year)	Reduction Coefficient (-)	
< 10,800	200mm Retum Period	< 10,000	100%
10,000 - 40,000	350mm Retum Period	10,000 - 40,000	75%
40,000 - 80,000	500mm Retum Pariod	40,000 - 80,000	50%
> 100,000	650mm Retum Period	> 80,000	25%

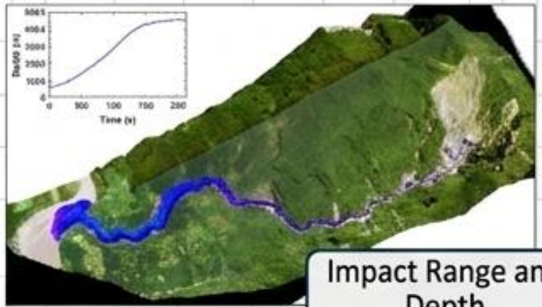
Note: The reduction coefficient (:) ie based on RAMMS almuistion experience, determined by unetable sediment velume and rainfall Return Period (year).

RAMMS Numerical Simulation

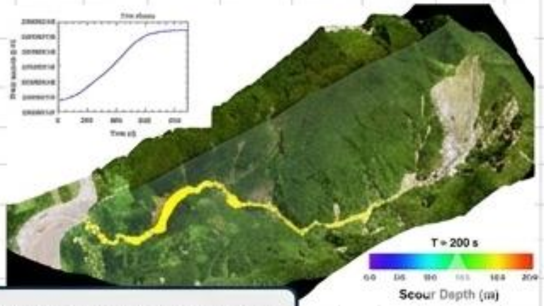


Debris Flow Runout Impact Range and Depth Map

Yu-Huei River Numerical Simulation



Impact Range and Depth



River Bed Scour Depth

Impact of Unstable sediment runout simulation

Yusui River debris flow simulation in 2021 Typhoon Lupit

- Simulation erosion depth:~ 5m

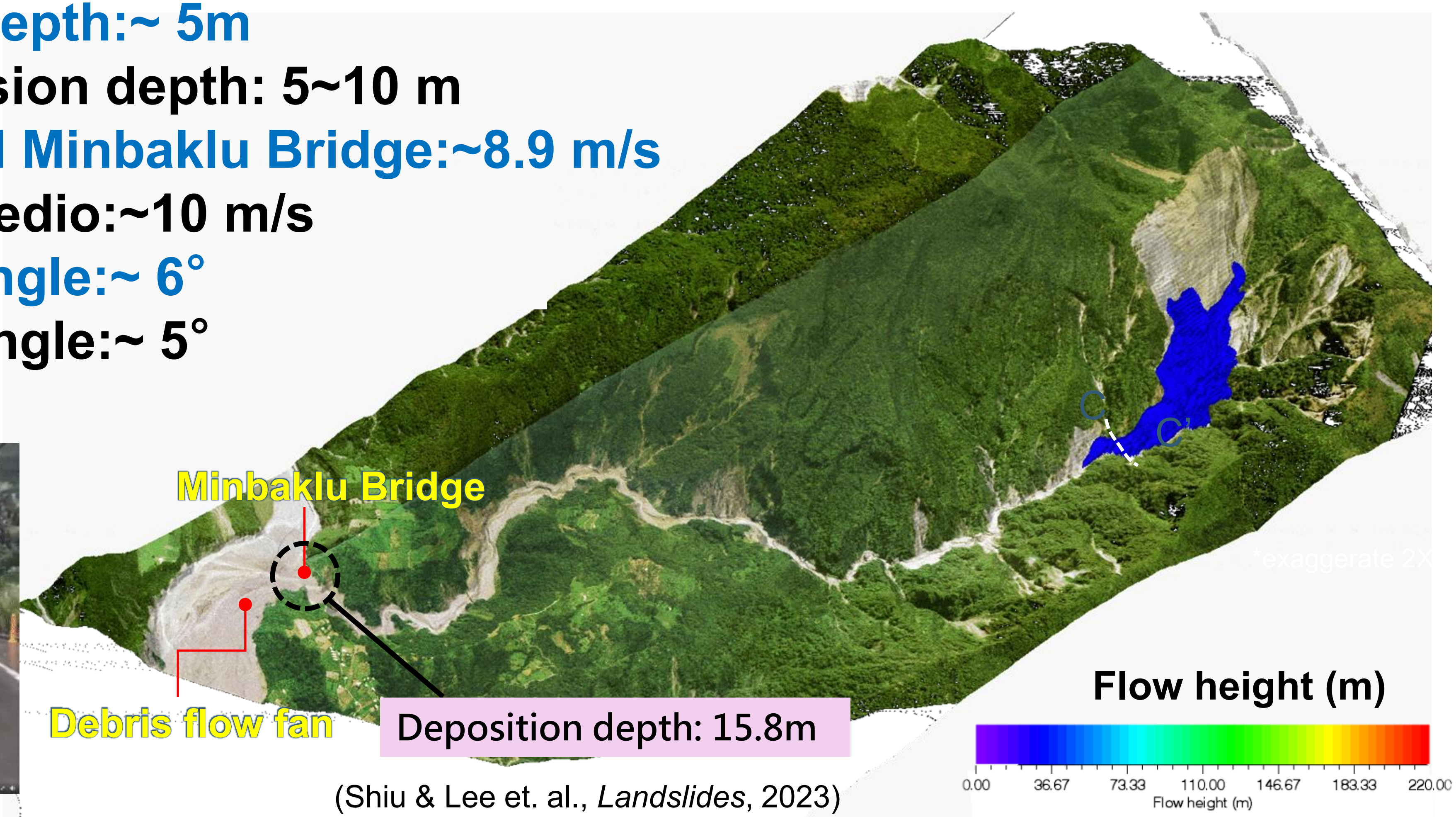
→Post-event topo erosion depth: 5~10 m

- Flow velocity around Minbaklu Bridge:~8.9 m/s

→Flow velocity from vedio:~10 m/s

- Simulation repose angle:~ 6°

→Post-event repose angle:~ 5°

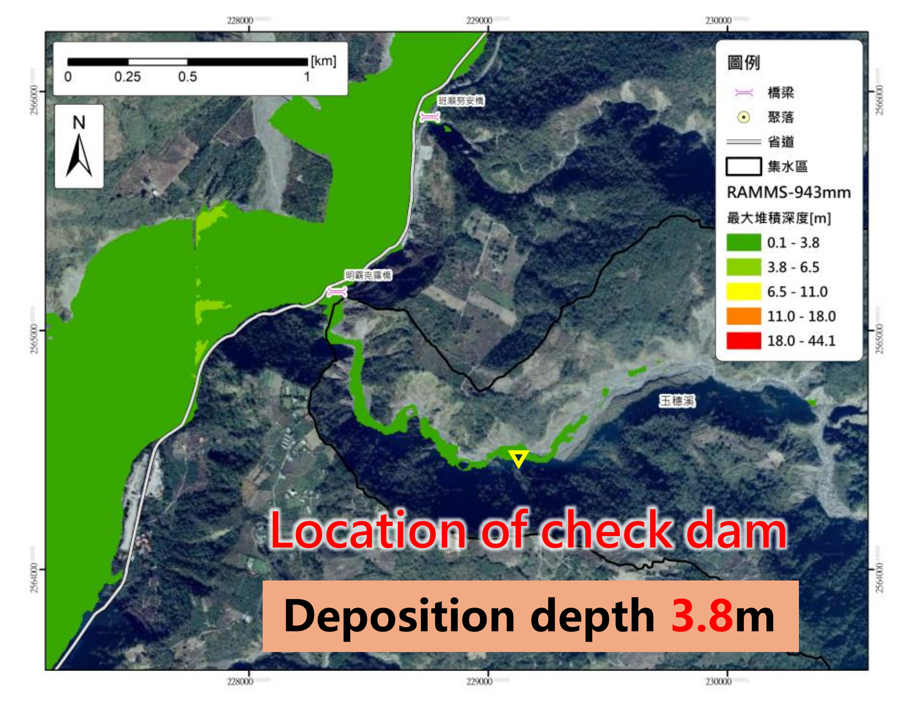


(Shiu & Lee et. al., *Landslides*, 2023)

Impact of Unstable sediment runout simulation

Calibration and parameter adjustment

- Comparison of pre-(2021) and post-(2024) DEMs to validate the predictive capability of the model.
- Reduction coefficient of residual sediment on slopes
  - Activity, sediment delivery rate, rainfall intensity
- Reduction coefficient of new landslide sediment on slopes
  - The age of landslide, sediment delivery rate, rainfall intensity
- The simulated and in-situ deposition depths near the check dam after Typhoon Gaemi was 3.8 and 4 m, respectively.



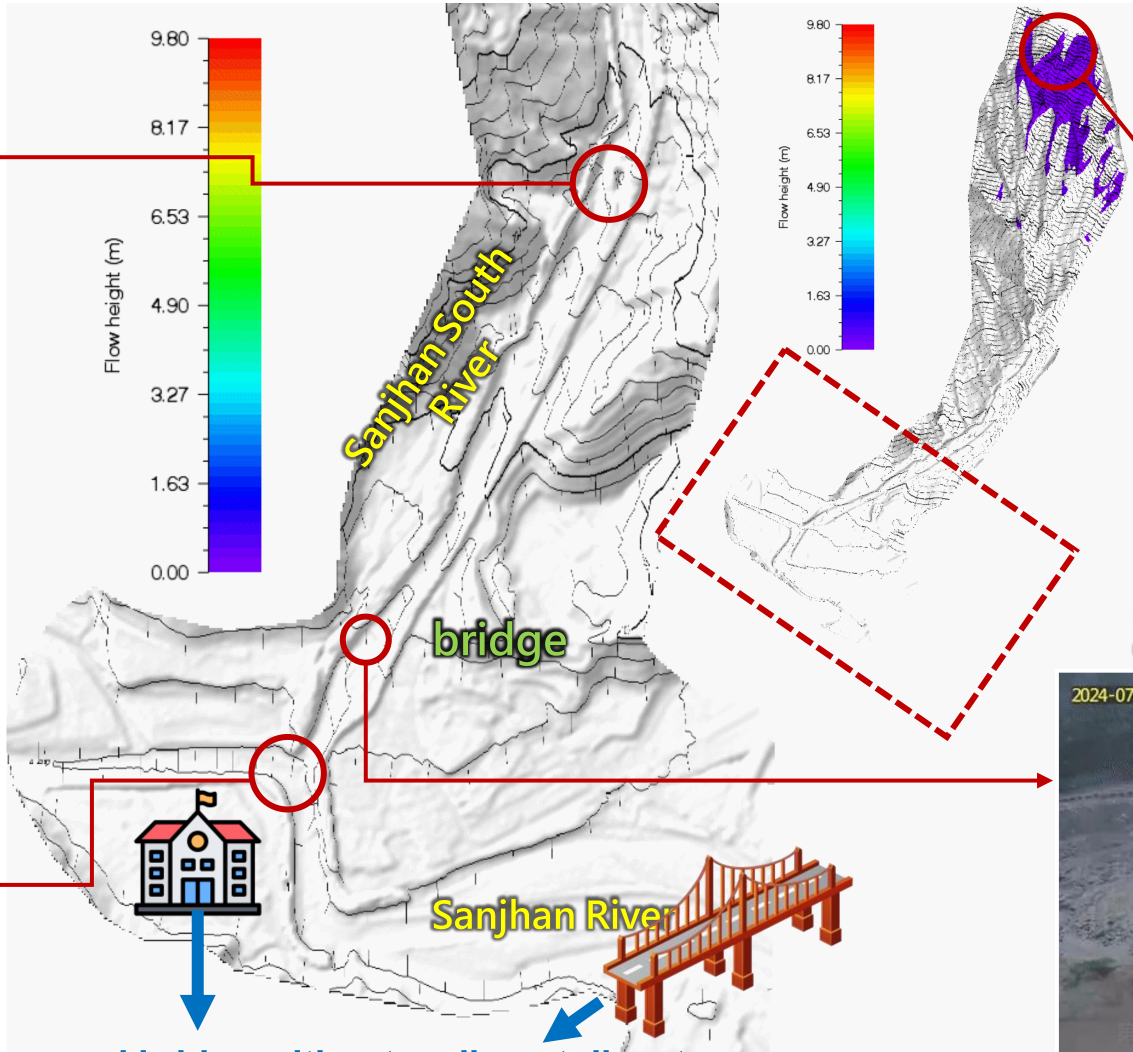
Before Typhoon Gaemi

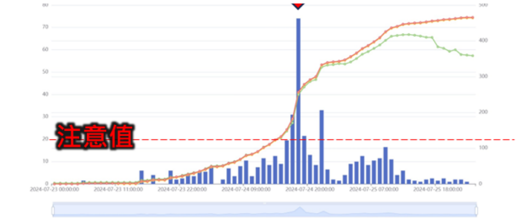
After Typhoon Gaemi

Unstable sediment runout simulation–Sanjhan South River

Max. Rainfall 86.5 mm/hr
Accum. Rainfall 307.5 mm

validated under 350 mm of rainfall





Downstream village and bridge without sediment disaster

Conclusions

1. Residual Slopes were identified by the integration of topographic features, DoD, and multi-temporal satellite imagery.
2. The volume, activity, and hazard were used to level runout potential of unstable sed. catchment in Taiwan.
3. Evaluation of runout potential of Residual Slopes can help us Quickly screening priority location of unstable sediment.
4. Structural measures can mitigate the unstable sediment runout impact; their long-term performance is depending upon regular maintenance.

Discussion - Further Research

1. A total of 552 residual slopes were identified, which will evolve over time and representing potential sources for future sediment-related disasters.
2. Due to limited temporal resolution of available DEMs (2010-2013 and 2016-2020), periodic monitoring data is still required for the accurate activity estimation of residual slopes.
3. Further research is needed to address the problems of
   ① Remobilization of unstable sediment on residual slopes,
   ② Kinematic assessment of residual slopes,
   ③ Potential volume of unstable sediment.

報 告 完 畢
敬 請 指 教

Thank you for your listening

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