INSTITUTE OF MOUNTAIN HAZARDS AND ENVIRONMENT,
CHINESE ACADEMY OF SCIENCES

中国科学院大学
University of Chinese Academy of Sciences

EGU2022 NH3.1 Debris flows: advances on mechanics, controlling factors, monitoring, modeling and risk management

Integrated numerical modeling of a large debris flow in the Meilong catchment, China

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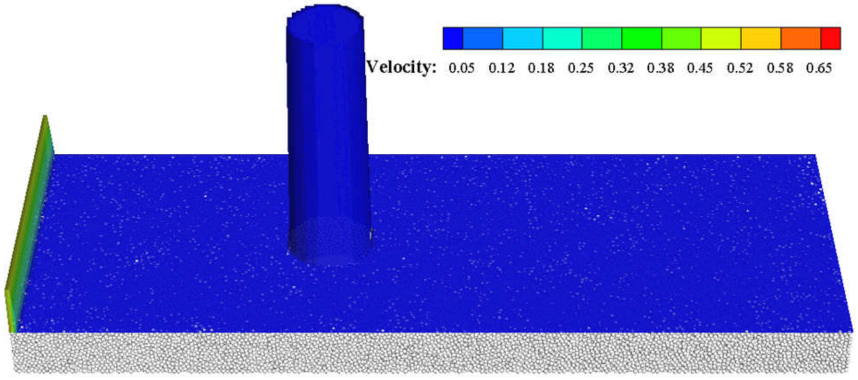
Background

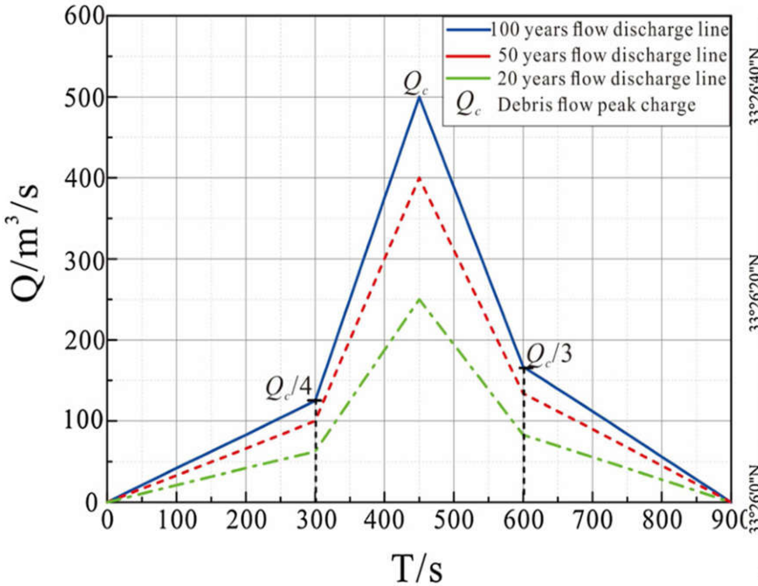
- **The role of numerical simulation in debris flow risk reduction**

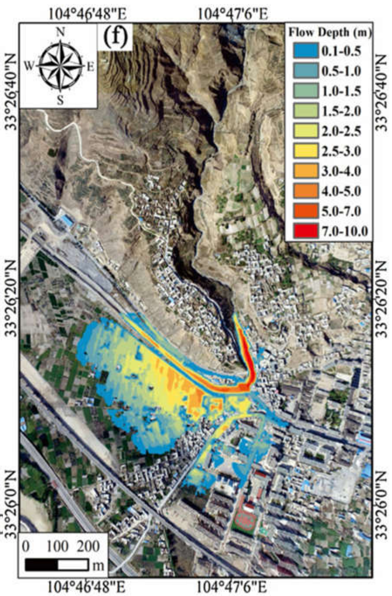


Risk assessment of debris flow

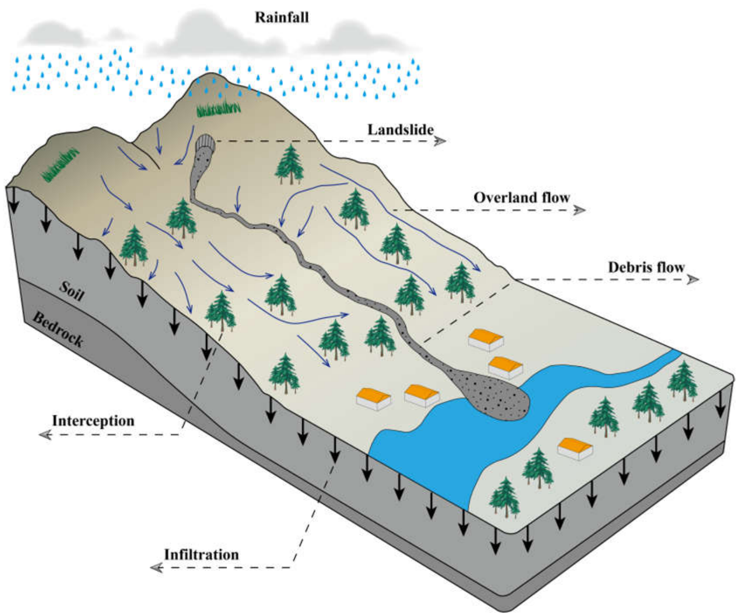
Forecast of debris flow

- **Research gap**



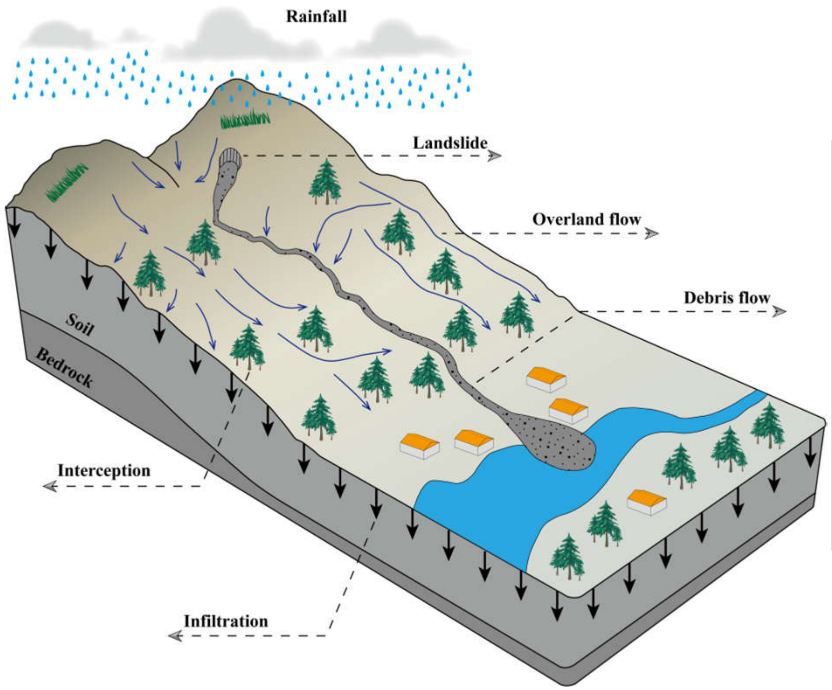


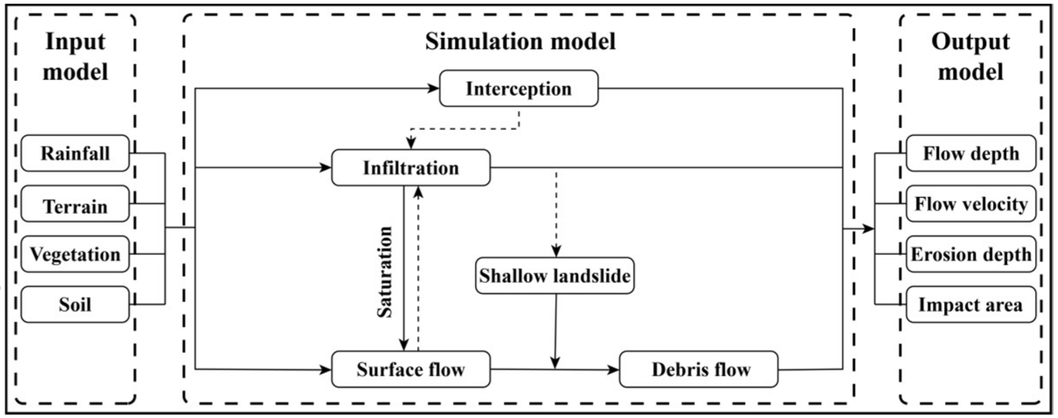
Way 1: Flow hydrograph (initiation of debris flow is ignored)



Way 2: Multiple physical processes

Methods





Flowchart of the integrated numerical model

Process	Vegetation interception; Soil infiltration; Slope stability; Surface flow; Erosion
Model	Aston; Richard; Infinite slope; Shallow water and two-phase flow equations
Implementation	Numerical implementation; CPU+GPU implementation
Case	1D infiltration; 2D V-catchment; Flood; Debris flow

Interception

Aston (1979) studied the dynamics of the interception process by plant canopies through experiments and established the following empirical relationship:

$$I_c = S_{\max}\left[1-\exp\left(-kP_t/S_{\max}\right)\right]$$

where I_c is the current accumulated interception storage (mm), S_{max} is the maximum canopy storage (mm), P_t is the current accumulated precipitation (mm)

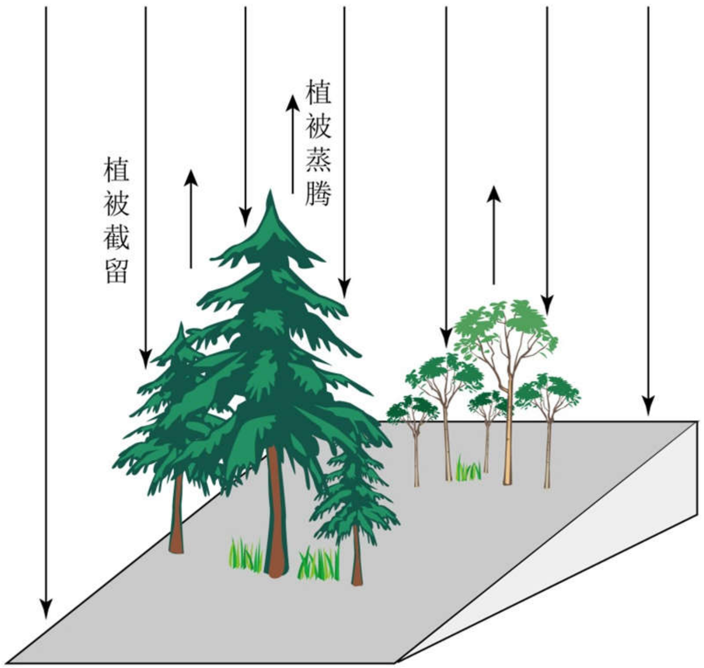


Diagram of the interception process

For the maximum canopy storage, equations for different land covers, depending on the leaf area index, are expressed as follows (von Hoyningen-Huene, 1983):

$$S_{\max} = \begin{cases} 0.935 + 0.498LAI - 0.00575LAI^2 & (Crops) \\ 0.2331LAI & (Pinus) \\ 0.3165LAI & (Douglas) \\ 1.46LAI^{0.56} & (Olive) \\ 0.0918LAI^{1.04} & (Eucalypt) \\ 0.2856LAI & (Broadleaved\ Forest) \\ 0.1713LAI & (Bracken) \\ 0.59LAI^{0.88} & (Clumped\ Grass) \end{cases}$$

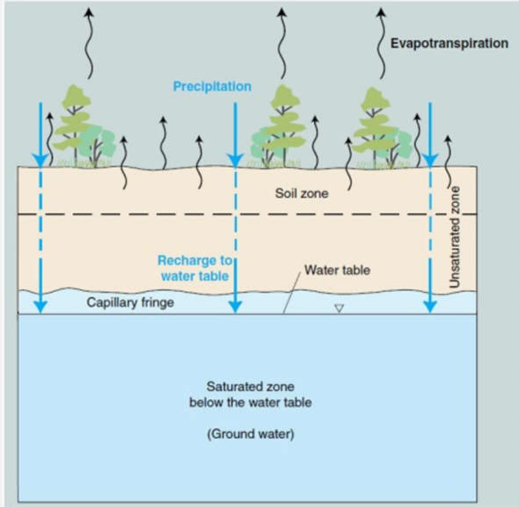
Soil infiltration and Surface flow

Richards equation

$$\left[C(h)+S_wS_s\right]\frac{\partial h}{\partial t}=\left\{\frac{\partial}{\partial x}\left[K_x(h)\left(\frac{\partial h}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[K_y(h)\left(\frac{\partial h}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[K_z(h)\left(\frac{\partial h}{\partial z}+1\right)\right]\right\}\pm Q_{ext}$$

$$K(h_s)=K_sK_r=\begin{cases} K_s(1+\beta)^{-5m/2}\left[(1+\beta)^m-\beta^m\right]^2 & for\quad h_s\le 0 \\ K_s & for\quad h_s>0 \end{cases}$$

$$C(h_s)=\begin{cases} \dfrac{(n-1)(\theta_s-\theta_r)|h_s|^{n-1}}{|h_a|^n\left(1+|h_s/h_a|^n\right)^{m+1}} & for\quad h_s\le 0 \\ 0 & for\quad h_s>0 \end{cases}$$

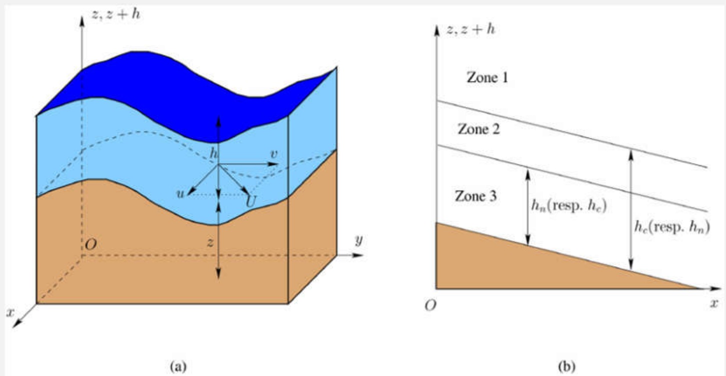


Shallow water equations

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=R-I$$

$$\frac{\partial hu}{\partial t}+\frac{\partial\left(hu^2+0.5gh^2\right)}{\partial x}+\frac{\partial huv}{\partial y}=-gh\frac{\partial z_b}{\partial x}-\frac{\tau_{fx}}{\rho}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial\left(hv^2+0.5gh^2\right)}{\partial y}=-gh\frac{\partial z_b}{\partial y}-\frac{\tau_{fy}}{\rho}$$



Debris flow

Two-phase flow equations

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=R-I+\frac{E-D}{1-p}$$

$$\frac{\partial hu}{\partial t}+\frac{\partial (hu^2+0.5gh^2)}{\partial x}+\frac{\partial huv}{\partial y}=-gh\frac{\partial z_b}{\partial x}-\frac{(\tau_{zx})_b}{\rho}$$
$$-0.5(\rho_s-\rho_f)\rho^{-1}gh^2\frac{\partial c}{\partial x}-(\rho_0-\rho)\rho^{-1}u(E-D)(1-p)^{-1}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial (hv^2+0.5gh^2)}{\partial y}=-gh\frac{\partial z_b}{\partial y}-\frac{(\tau_{zy})_b}{\rho}$$
$$-0.5(\rho_s-\rho_f)\rho^{-1}gh^2\frac{\partial c}{\partial y}-(\rho_0-\rho)\rho^{-1}v(E-D)(1-p)^{-1}$$

$$\frac{\partial hc}{\partial t}+\frac{\partial huc}{\partial x}+\frac{\partial hvc}{\partial y}=E-D$$

$$\frac{\partial z_b}{\partial t}=-(E-D)(1-p)^{-1}$$

Representing the evolution of the solid volume fraction and bed elevation

Erosion equation

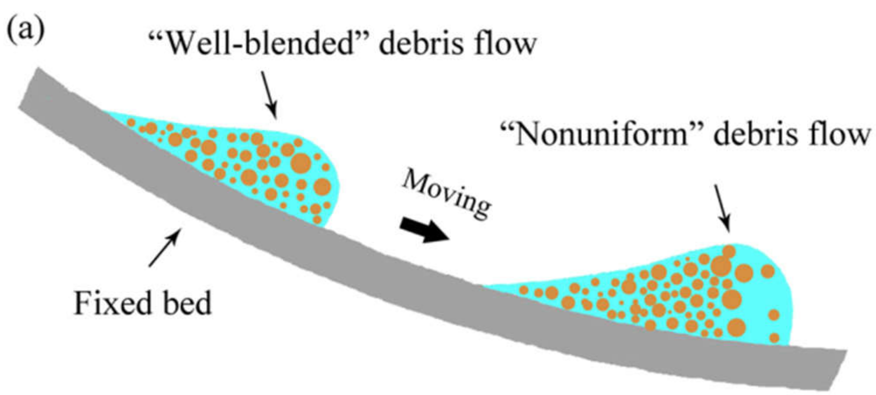
$$E=\frac{\tau_b-\tau_r}{\rho\sqrt{u^2+v^2}}$$

The sediment shear resistance:

$$\tau_r=c+(1-\lambda)\rho gh\tan\phi_{bed}$$

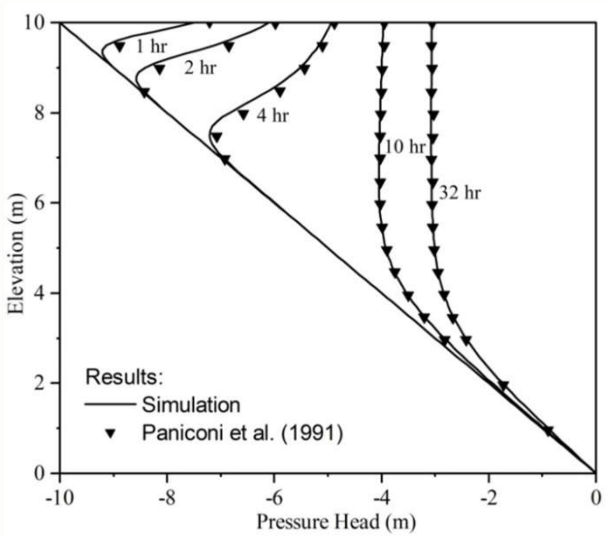
The total basal resistance:

$$\tau_b=\max\left[\tau_y+\frac{K\mu V}{8h}+\frac{\rho g n_{td}^2 V^2}{h^{1/3}},c\tau_{bs}+\left(1-c\right)\tau_{bf})\right]$$



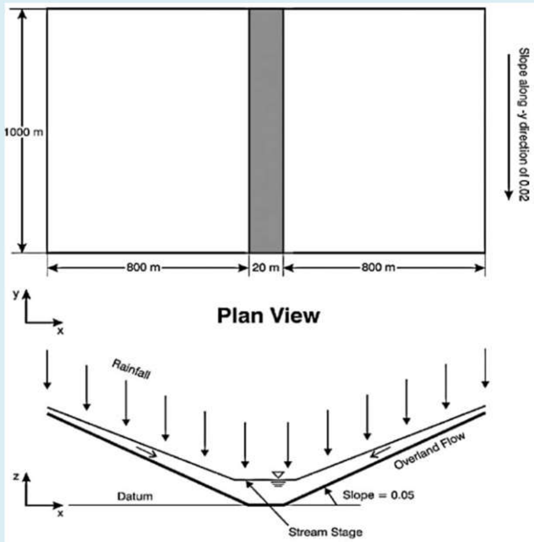
Verification

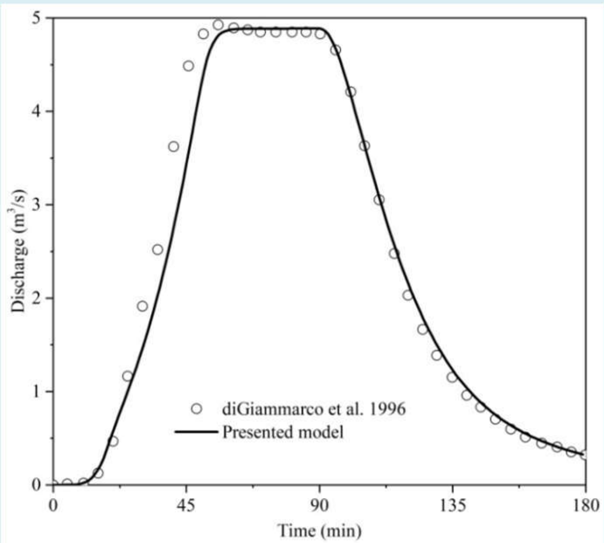
1D infiltration



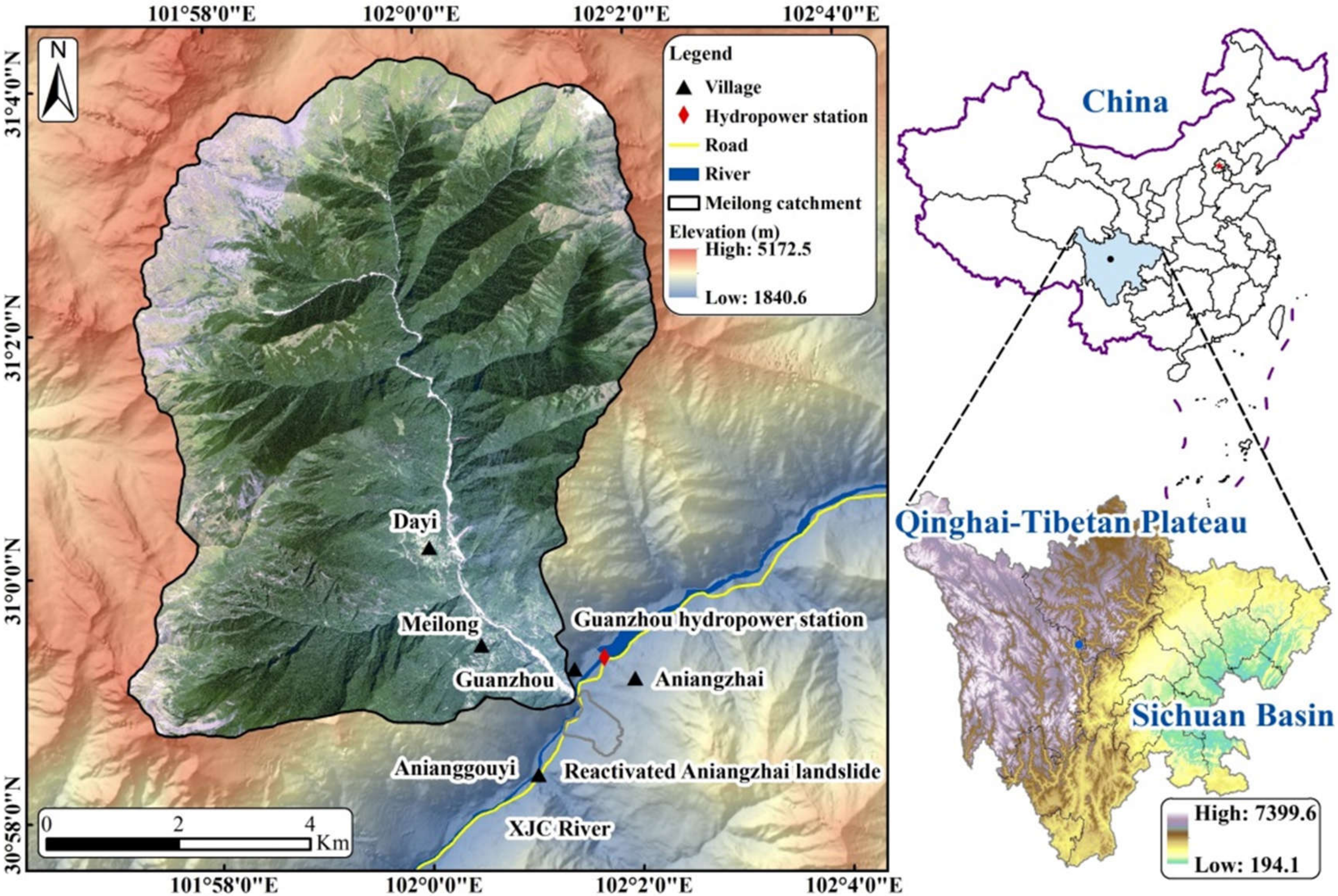
Parameter	Value or expression
Flow domain	10 m soil column
Saturated hydraulic conductivity K_s	5 $m \cdot h^{-1}$
Saturated moisture content ϑ_s	0.45 $m^3 \cdot m^{-3}$
Residual moisture content ϑ_r	0.08 $m^3 \cdot m^{-3}$
Air entry pressure head	-3.0 m
Van Genuchten parameter n	3
m=1-1/n	0.667
Specific storage S_s	0.001 m^{-1}
Top boundary condition	t/64 $m \cdot h^{-1}$
Bottom boundary condition	h=0 m
Initial pressure heads	h+z=0

2D V-catchment surface flow





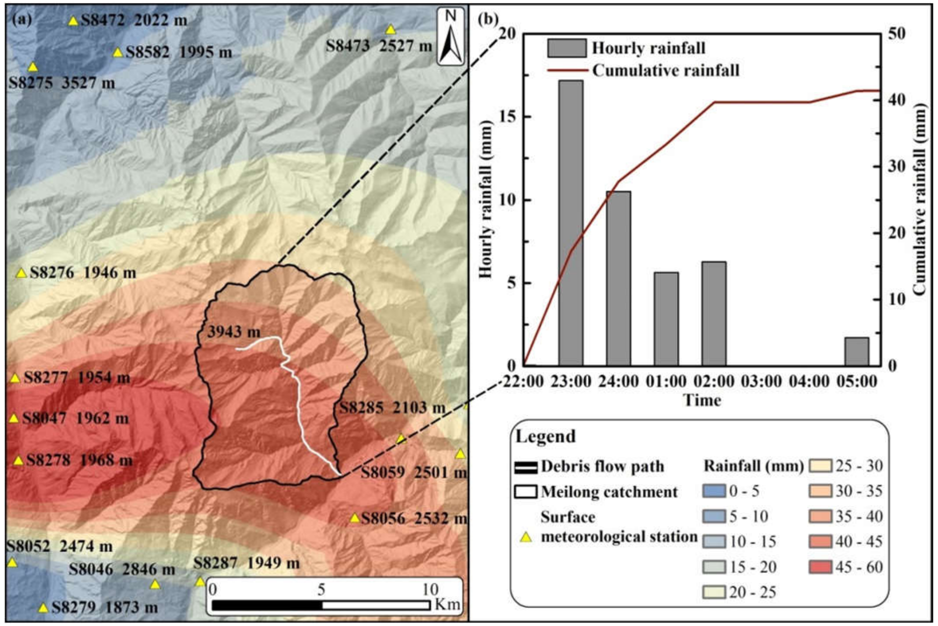
Meilong debris flow



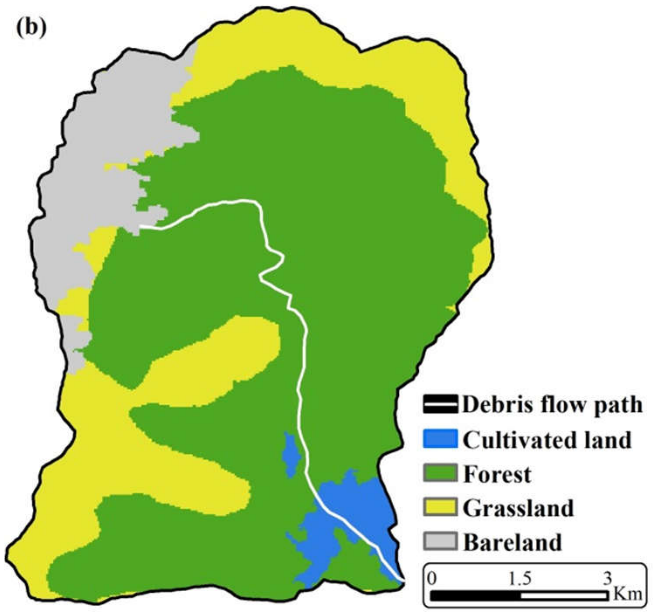
2020.6.17 Meilong catchment: shallow landslides-debris flow-flood

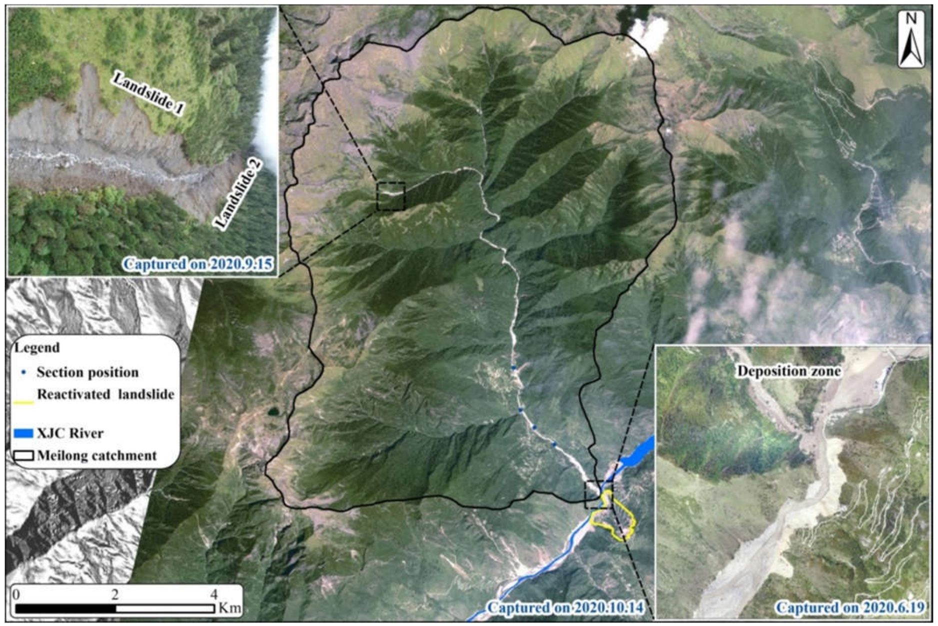
Field observation, Image interpretation, Laboratory experiments, Numerical simulation

Meilong debris flow



The rainstorm in the Meilong catchment lasted for approximately 4 h. The accumulated rainfall in the Meilong catchment was 39.6 mm. In terms of the intensity, the maximum value was 17.2 mm·h^{-1} during 23:00–24:00, accounting for 43.4% of the accumulated rainfall. In conclusion, this rainstorm can be characterized by short duration and high intensity.



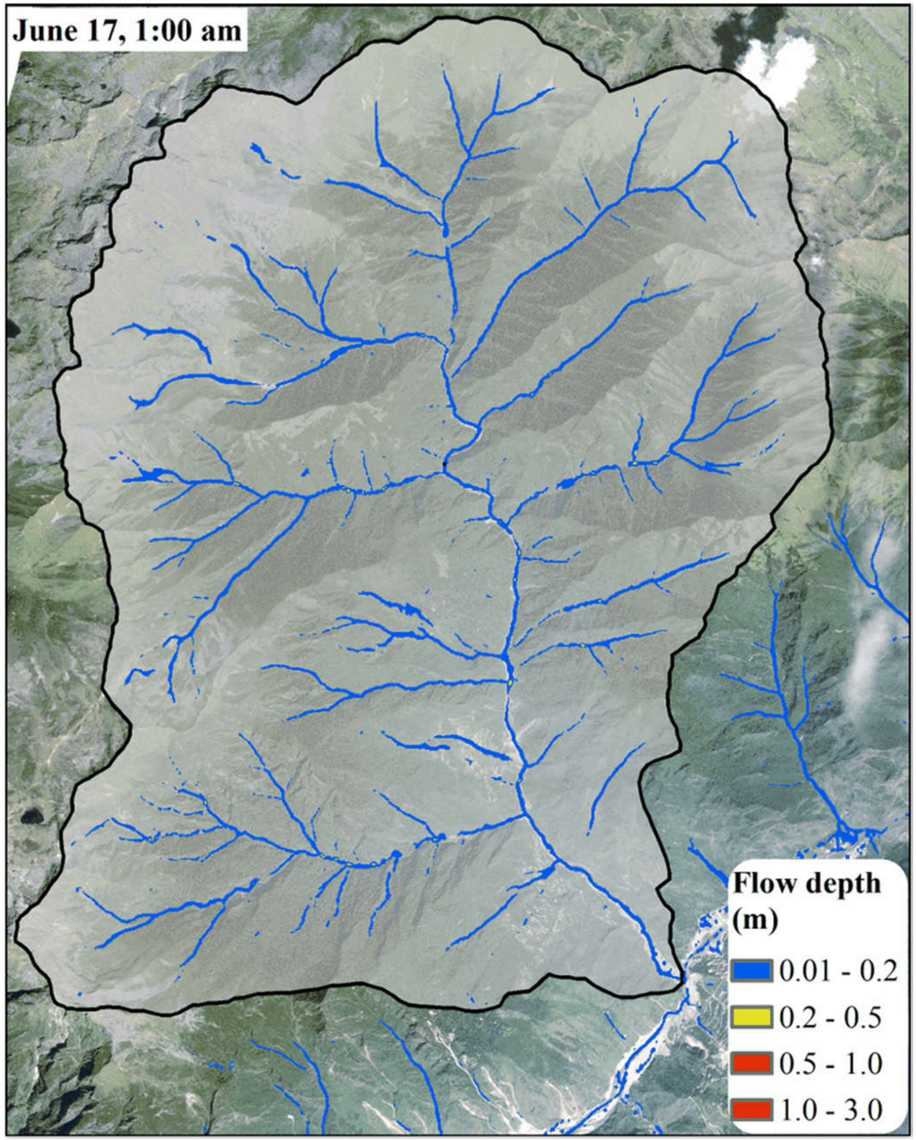


Meilong debris flow

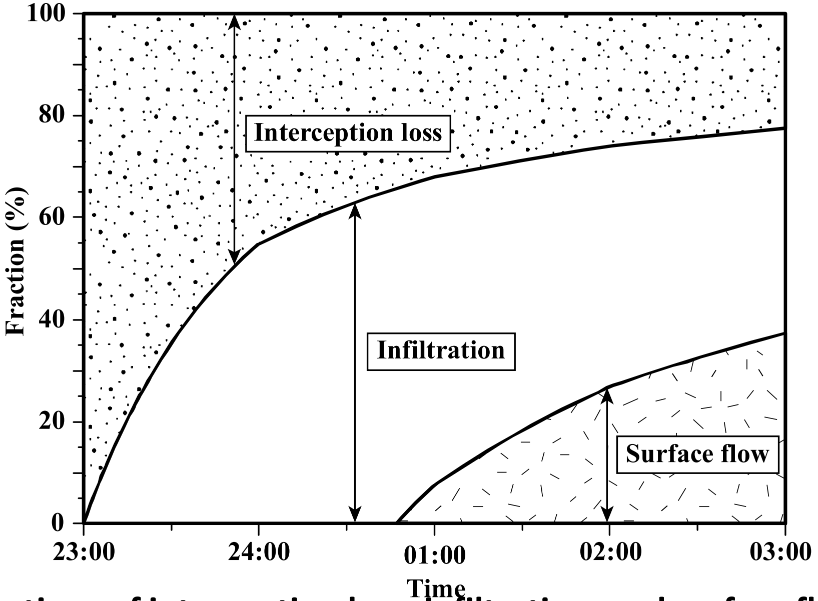
Parameters for the simulation

Model	Parameter	Value
Interception	Crown density *co*	0.8
	Leaf area index *LAI*	30.87
Infiltration	Saturated water content θ_s	0.5
	Residual water content θ_r	0.1
	Saturated hydraulic conductivity K_s	4.88×10^{-6}
	The shape parameter n	1.22
	Air entry pressure head h_a	0.47
	Specific storage S_s	1×10^{-4}
	Initial surface water content θ_0	0.3
Surface flow	Soil cohesion c_o	5000
	Soil internal friction angle φ_{bin}	30
	Pore pressure ratio η	0.8
	Coulomb basal friction angle φ_{bed}	15
	Manning coefficient n	0.035
Else	Density of water ρ_w	1000
	Density of solid ρ_s	2650

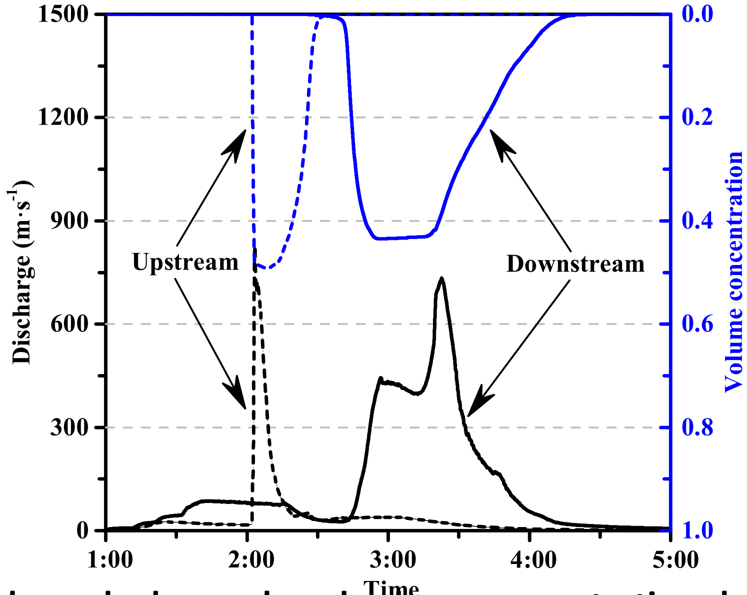
Flow depths during the entire rainfall process



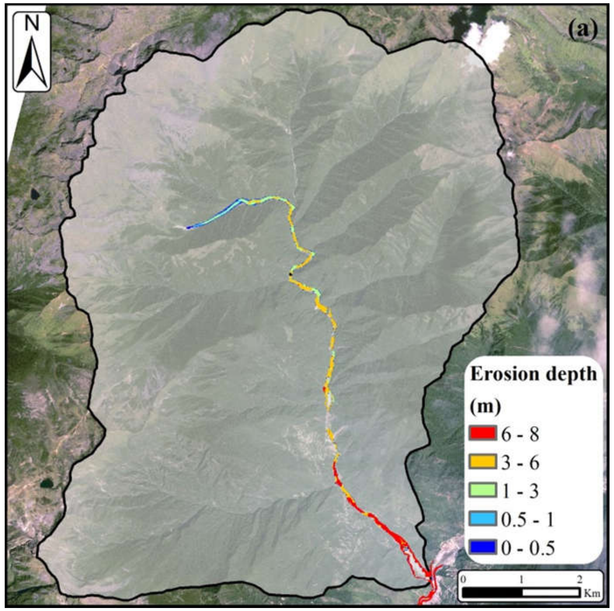
Meilong debris flow



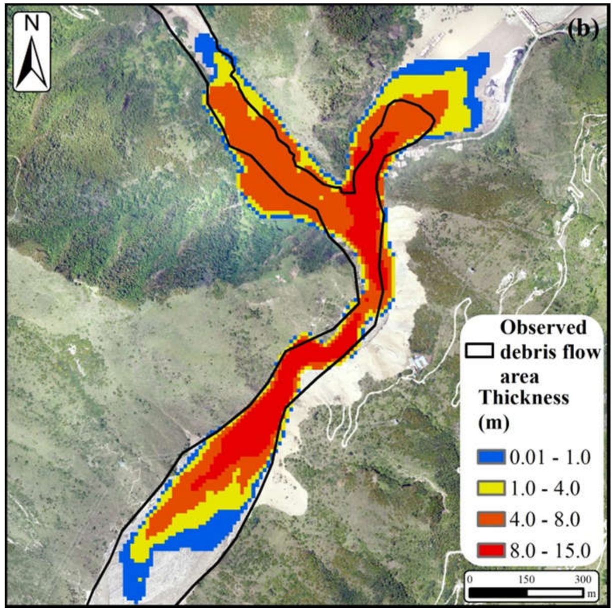
Fractions of interception loss, infiltration, and surface flow



Discharge hydrograph and volume concentration change



Simulated erosion depth along the main gully



Comparison of the deposition thickness with field observations

Thank you for your attention

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