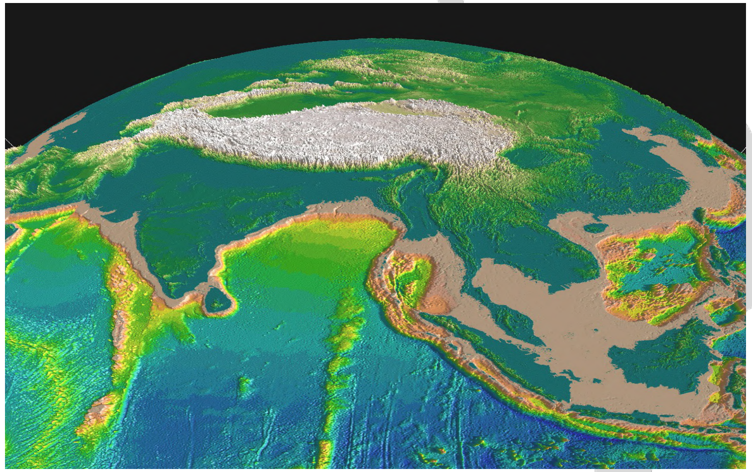
Mechanisms and Prediction of Earthquake and Climate Change Induced Cascading Hazards

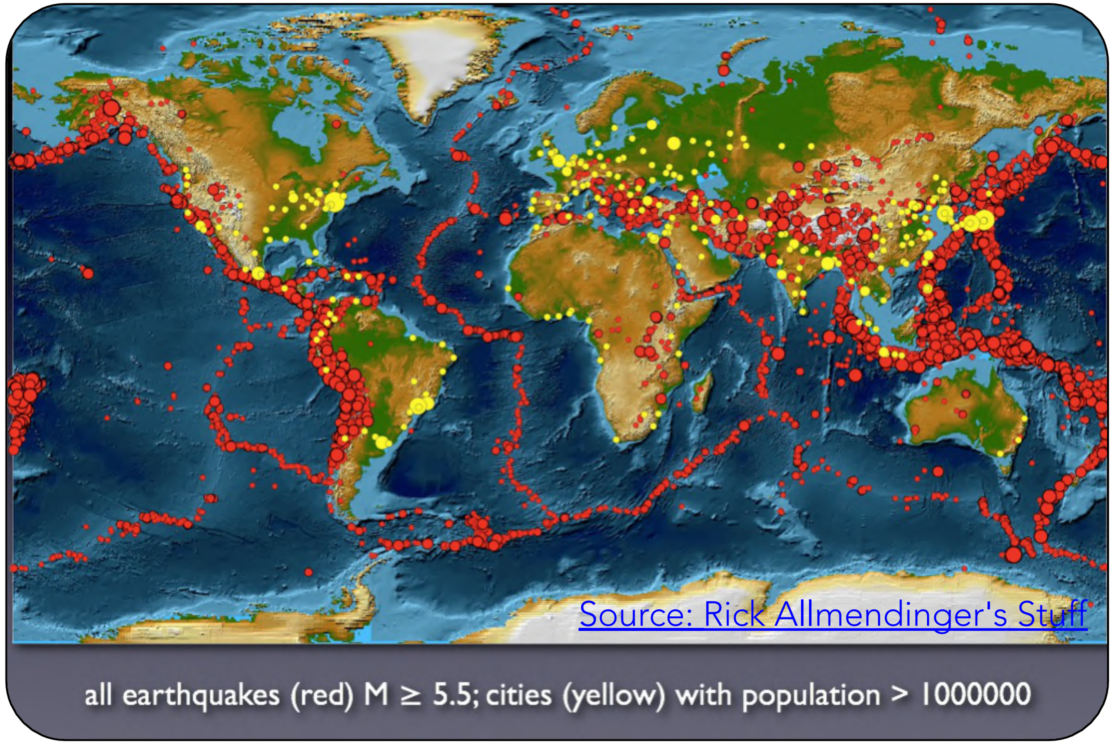
Xuanmei Fan



State Key Laboratory of Geohazard Prevention and Geoenvironment Protection
Chengdu University of Technology, Chengdu, Sichuan, China

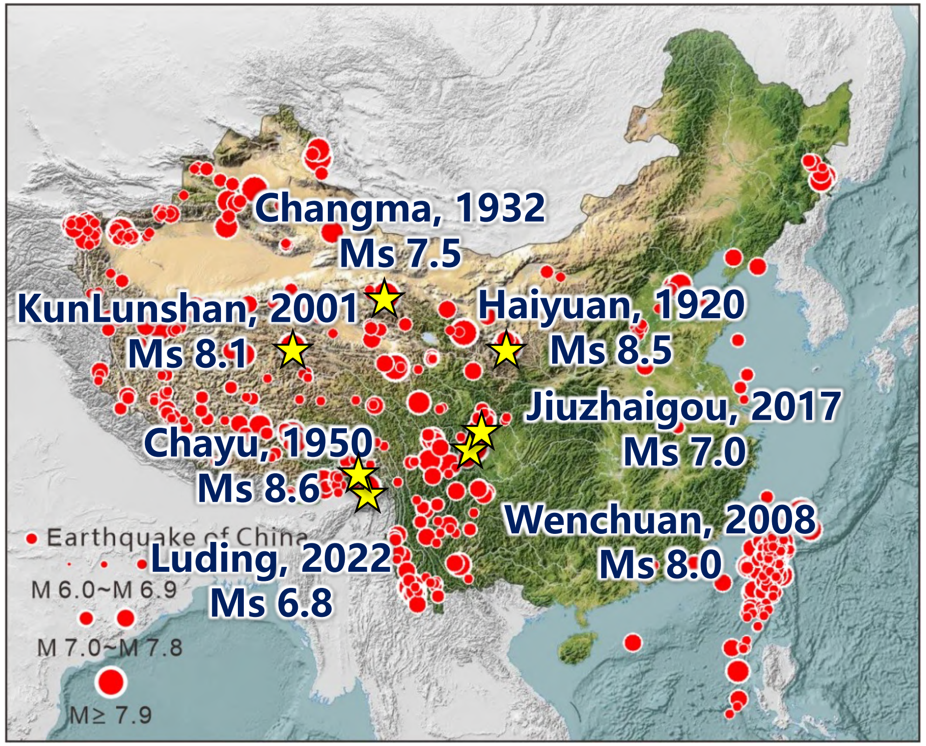
Strong earthquakes are the primary triggers of geological hazards

Global Earthquakes and Major Cities



A substantial proportion of the world's largest cities lies in regions with significant seismic risk.

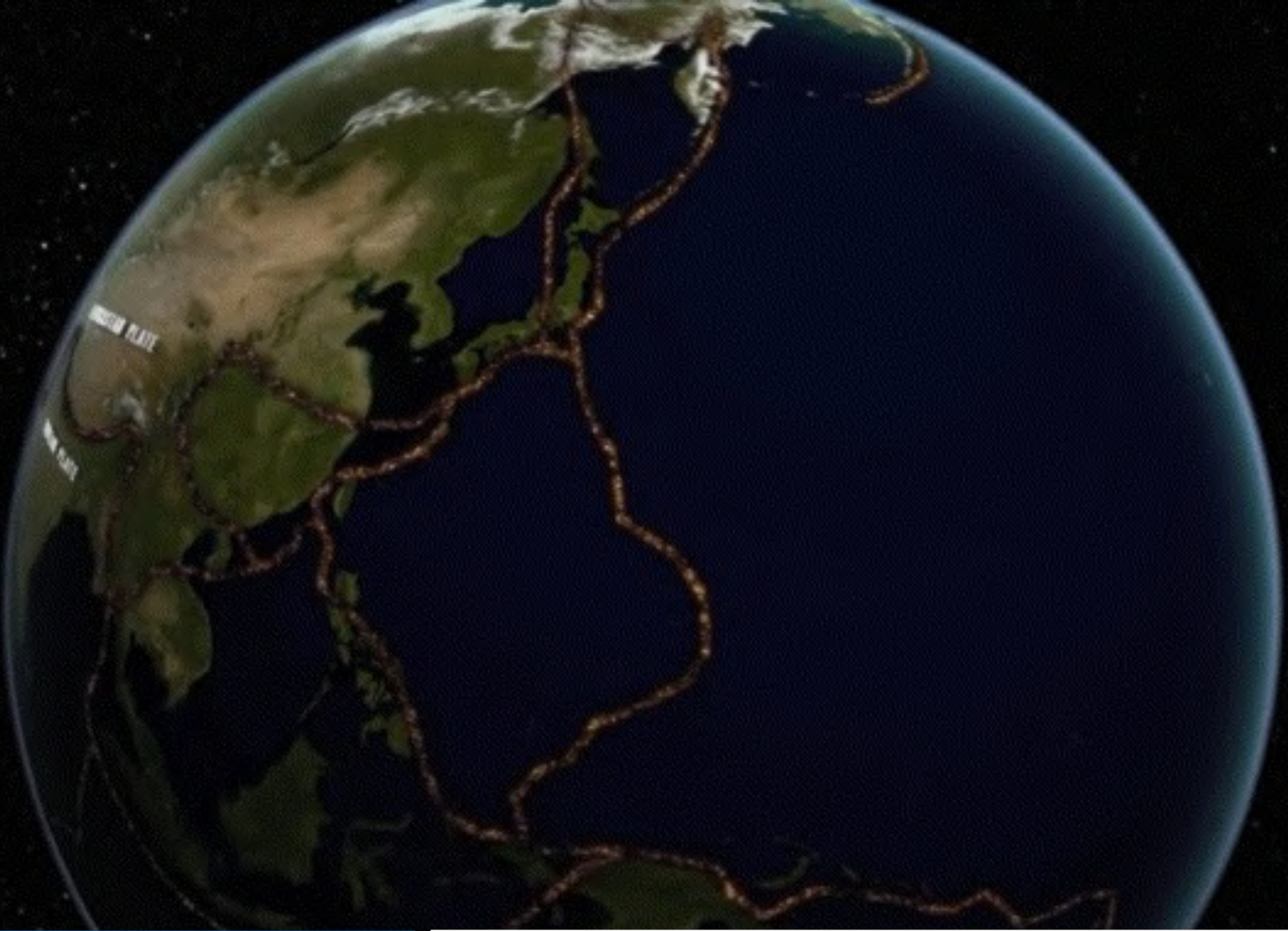
Distribution map of earthquakes in China



The main reasons for death toll are:

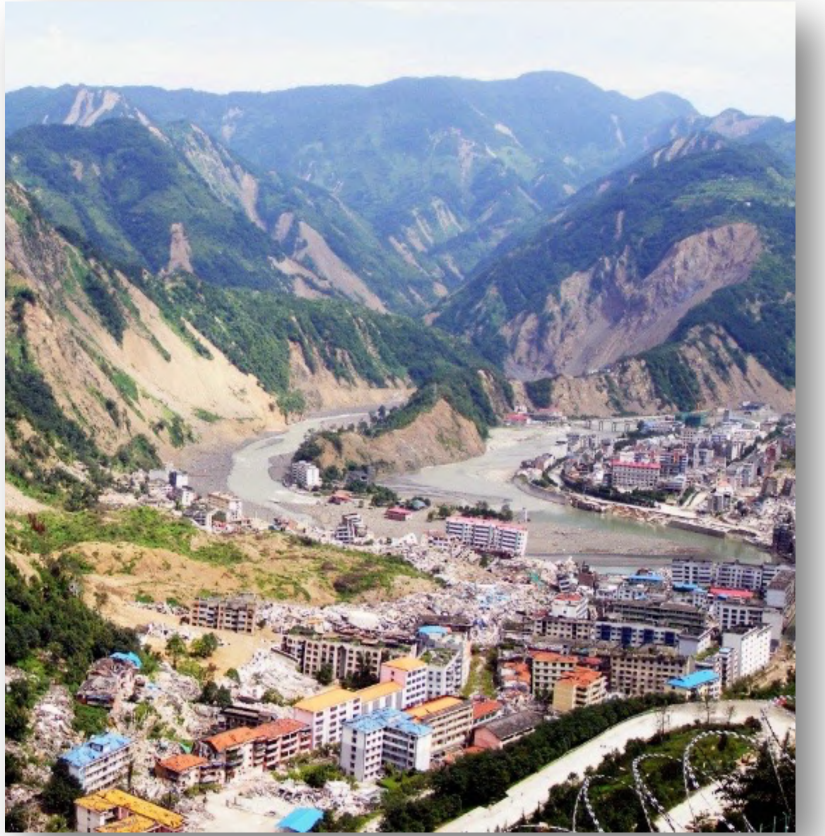
(1) Earthquake-caused collapse of buildings

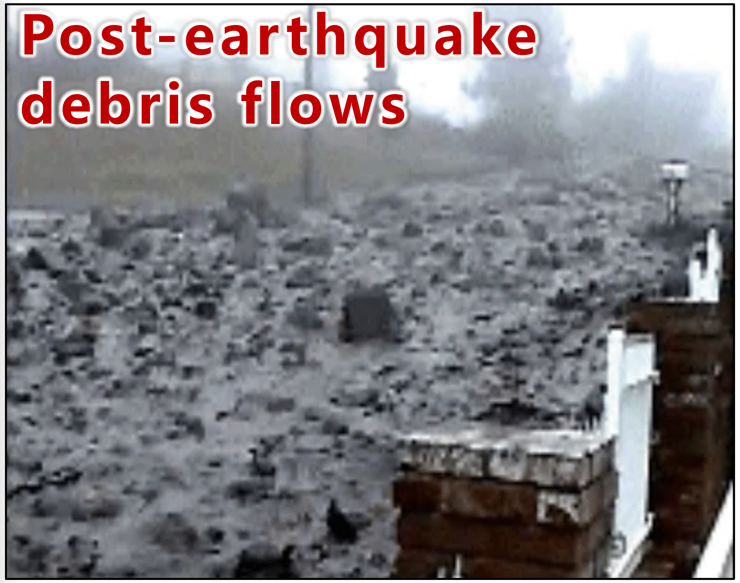
(2) Earthquake-induced landslides

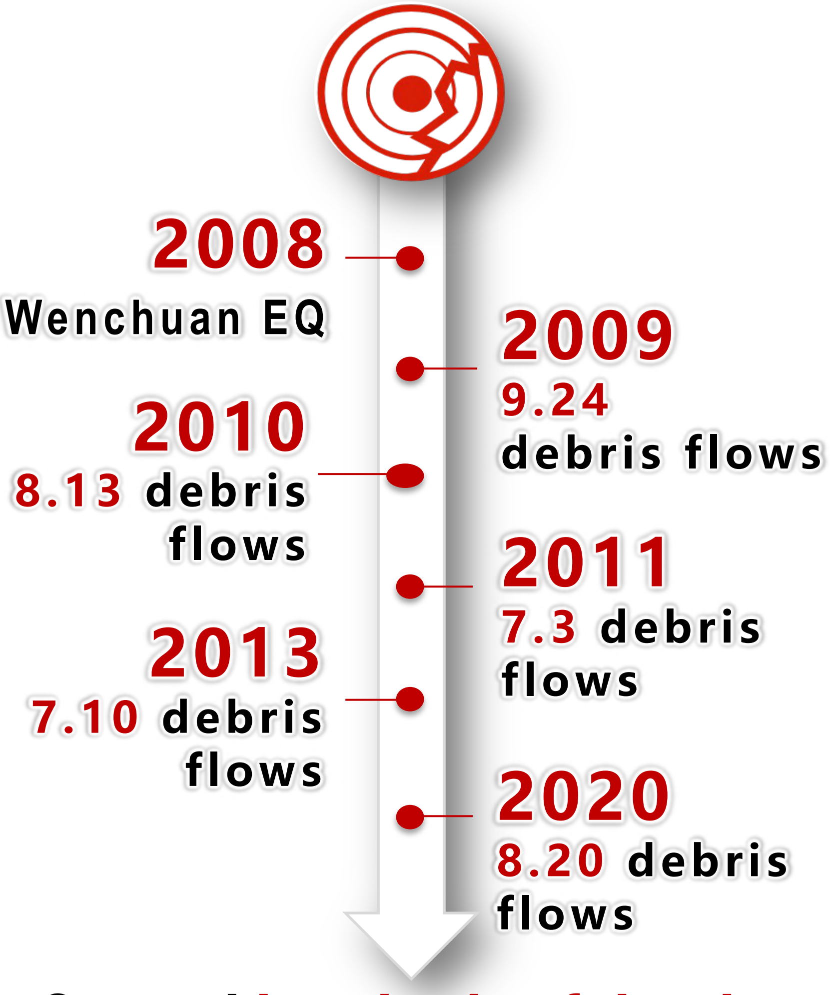


Earthquake-induced hazards have strong cascading effects

The 2008 Wenchuan earthquake triggered >200,000 landslides







Caused hundreds of deaths and over 10 billions RMB of economic loss

Main Challenges

Earthquake → Coseismic landslides → Landslide dams → Dam-breach flood

- The failure mechanism of earthquake-triggered large landslides is poorly understood;
- There is no models that can accurately predict the coseismic landslides and landslide dams

Coseismic landslides → Post-earthquake remobilized landslides → Post-earthquake Debris flows

- Post-earthquake landslides and debris flows have dynamic mechanism, evolving with time
- Early warning of post-earthquake debris flows is challenging

Key Findings

Finding 1

Prediction of coseismic landslides and dam-breach flood

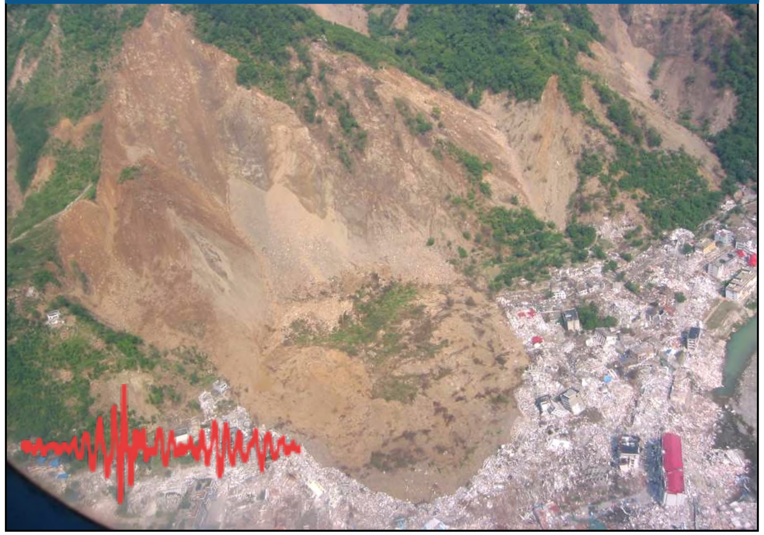
Finding 2

Mechansims and predition of post-seismic landslides and debris flows

Finding 3

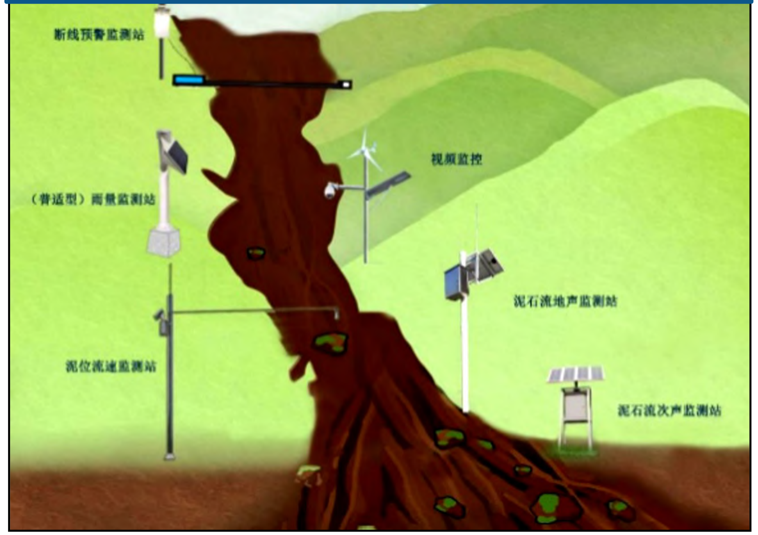
Early warning model of future chains of geololgical hazards

Coseismic hazards



Post-seismic debris flows

Early warning



Challenges：

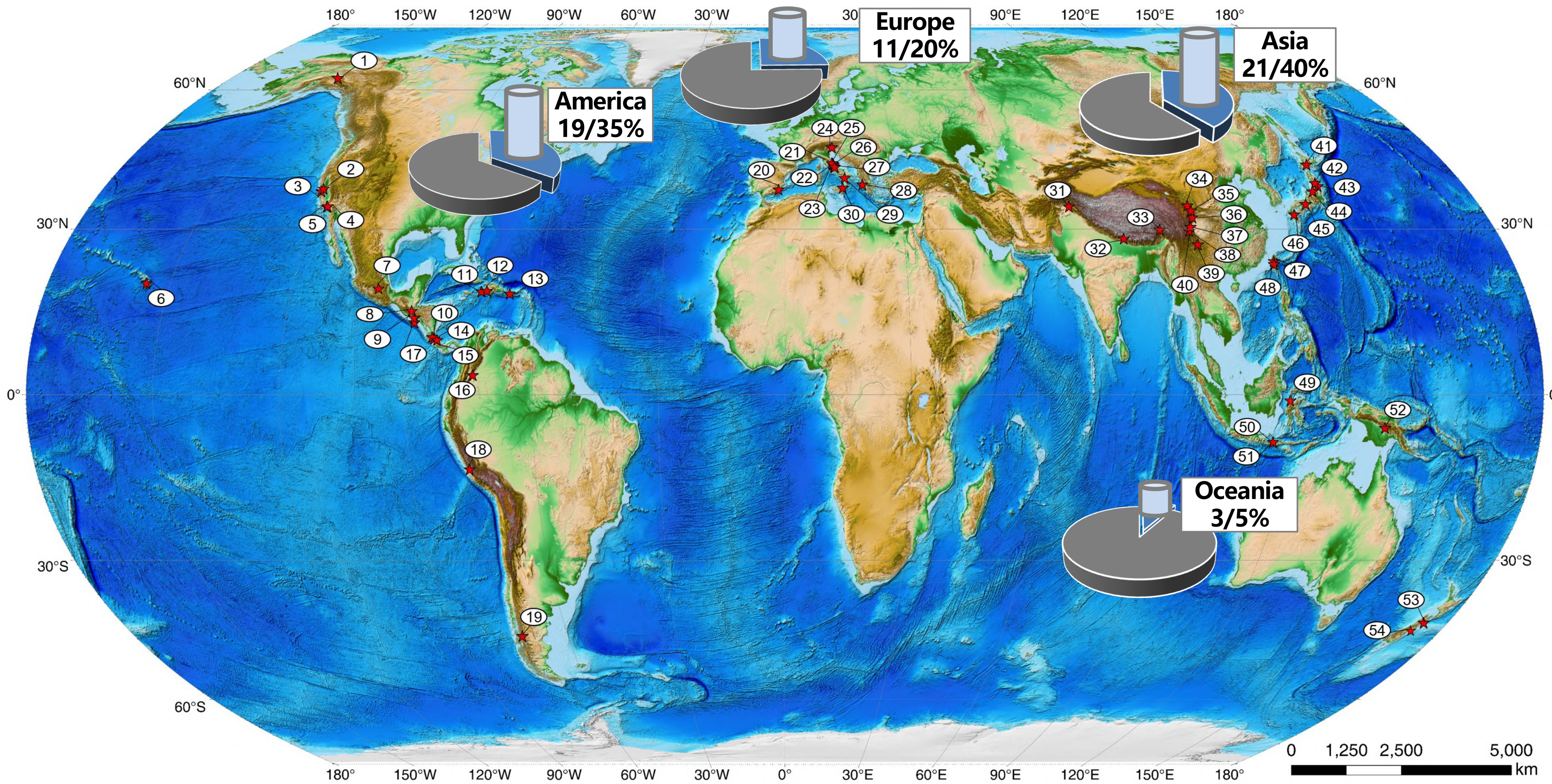
How to predict coseismic landslides?

How to predict dam-breach flooding risk?

https://www.hrr.mlit.go.jp/bosai/110920kasenbu/kekkai.html

Coseismic landslide prediction

◻ Global earthquake-triggered landslide inventory



- **54 historical strong earthquakes**
- **including more than 400,000 coseismic landslides**

Acknowledgment: Hakan Tanyaş and many others who contributed to the inventory

Hakan T et al., JGR: Earth Surface，2017
Fan et al., *Reviews of Geophysics*，2019

Coseismic landslide prediction

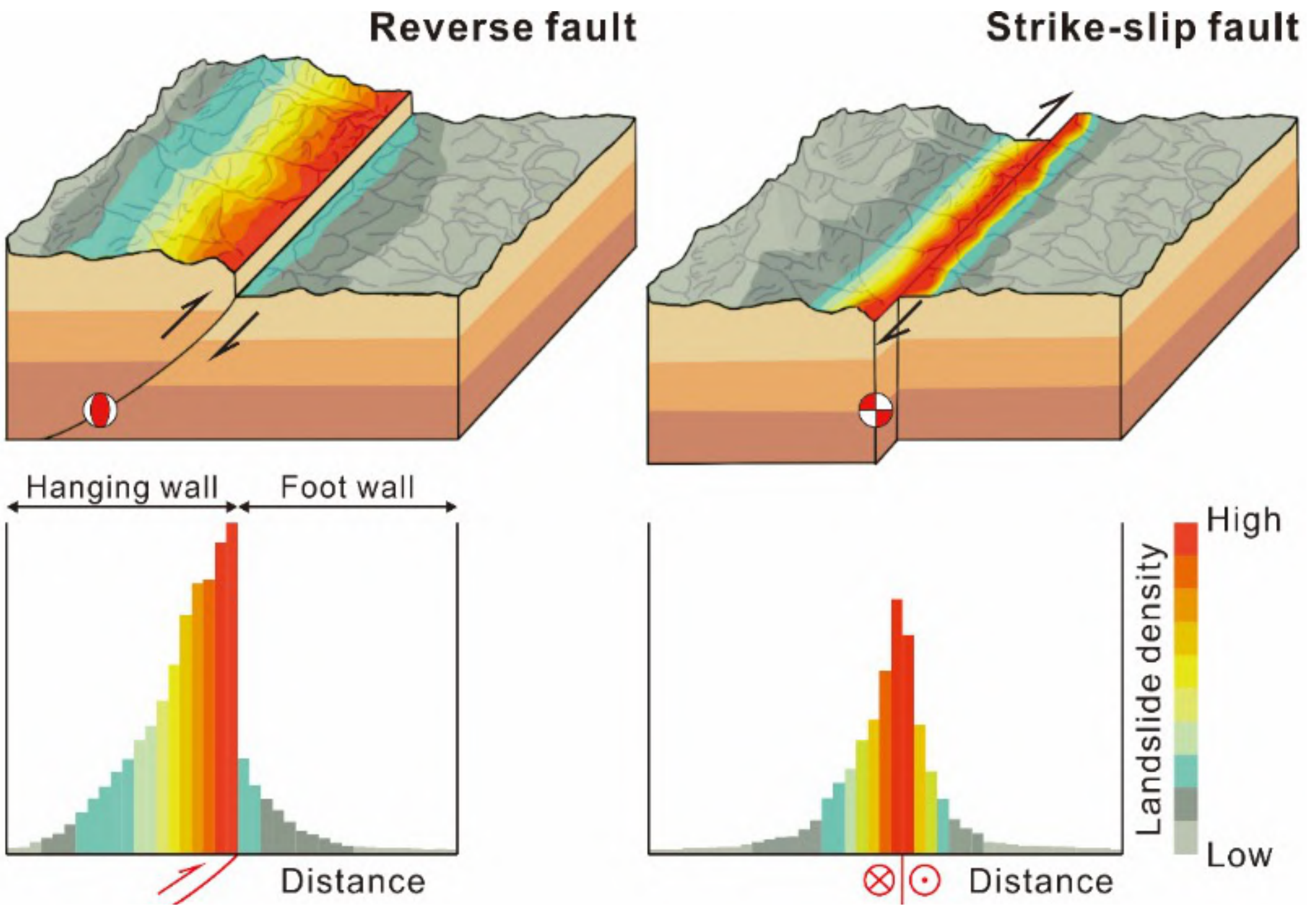
◻ Spatial distribution pattern and controls of coseismic landslides

◻ Controlling factors

Factors	
Seismic factors	▪***Distance to fault*** ▪***Fault type*** ▪***Hanging/foot wall effect*** ▪*Locking section effect*
Terrain factors	▪*Slope; Aspect* ▪*Internal relief* ▪*Micro-topography*
Geological factors	▪*Lithology* ▪*Geological structure*
Hydrological factors	▪*Distance to river* ▪*Stream power index* ▪*Drainage density*

Huang and Fan, *Nature Geoscience*, 2013

◻ Fault type, distance and hanging wall effect



Fan XM et al., *Reviews of Geophysics*, 2019

Coseismic landslide prediction

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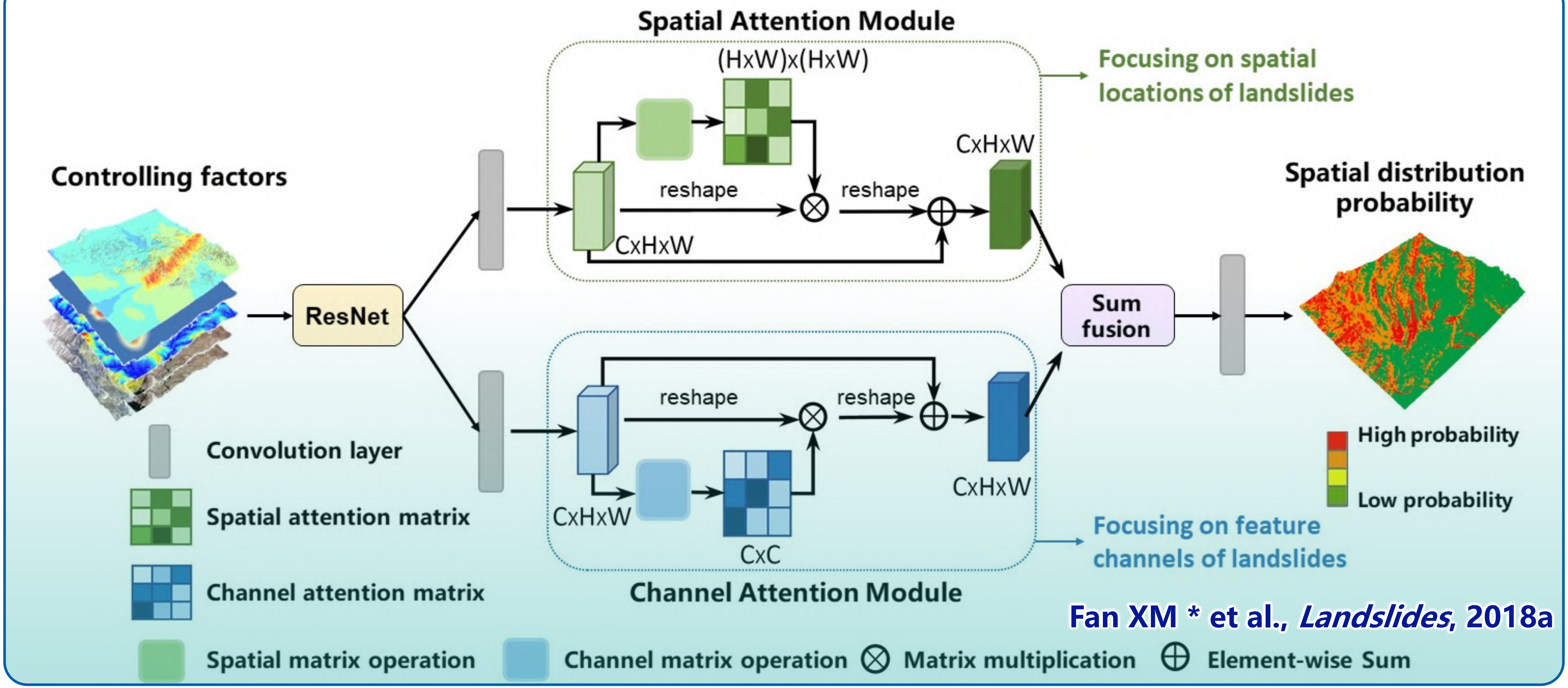
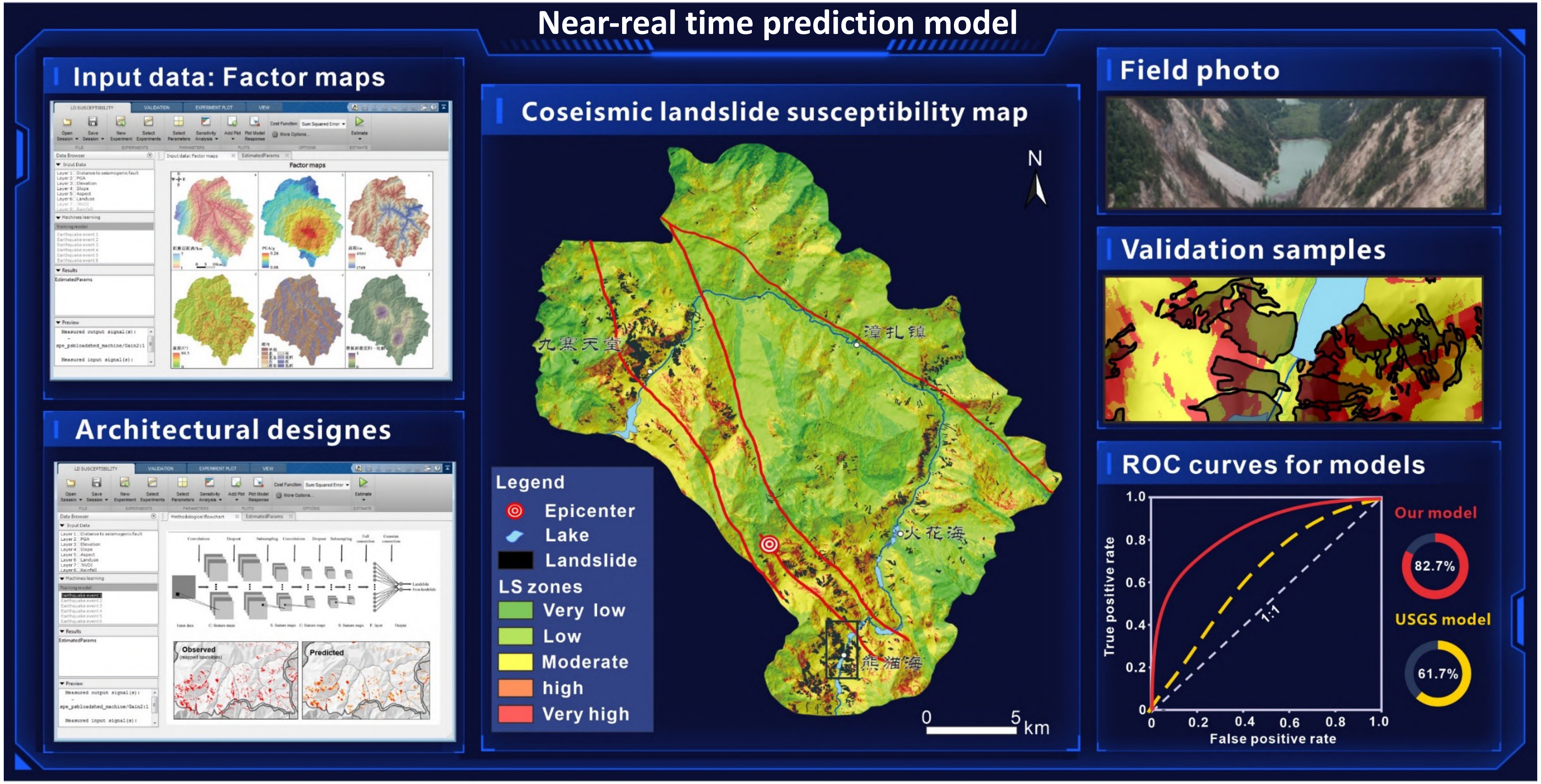
□ AI algorithms （CNN、 FCN (Fully Convolutional Network)、RF……)



Fan XM * et al., *Landslides*, 2018a

Coseismic landslide prediction

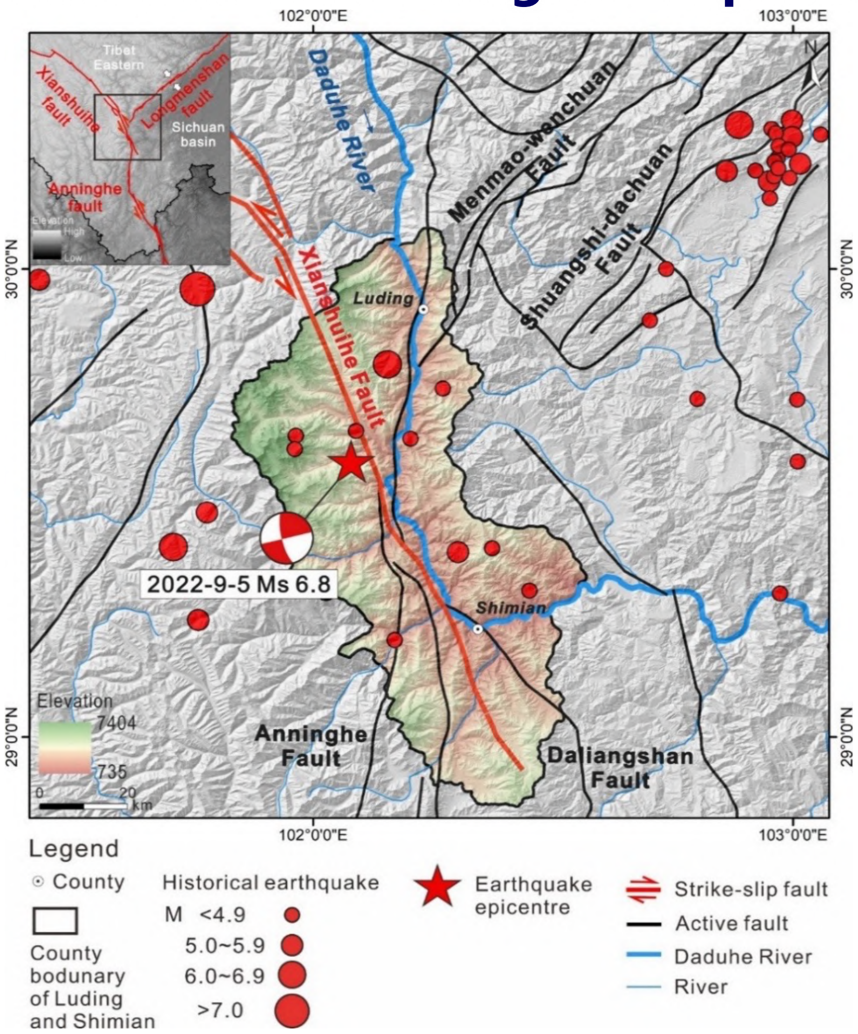
Near-real time prediction model of co-seismic landslides



Fan XM * et al., *Landslides*, 2018a

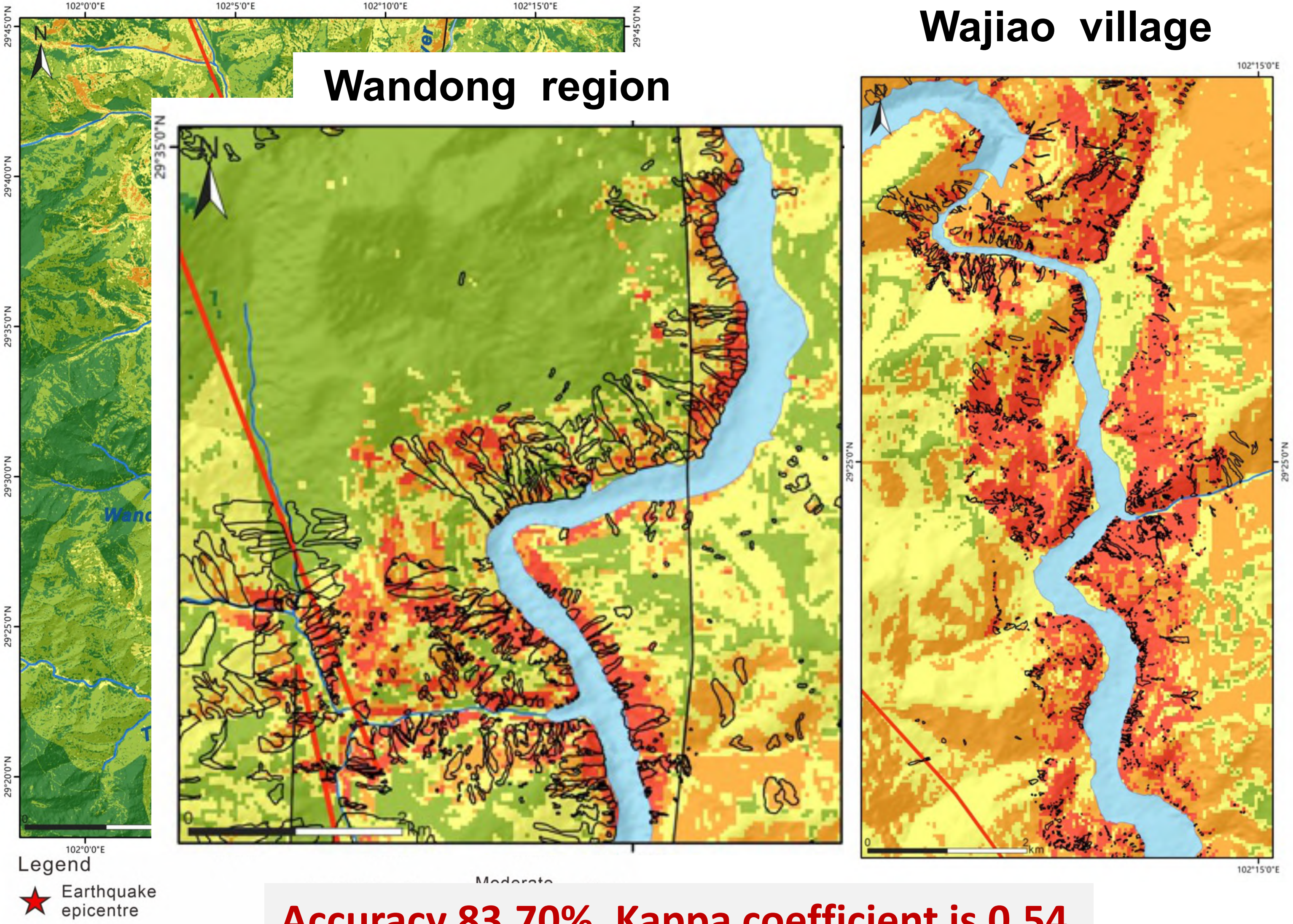
Coseismic landslide prediction

2022 Ms 6.8 Luding earthquake

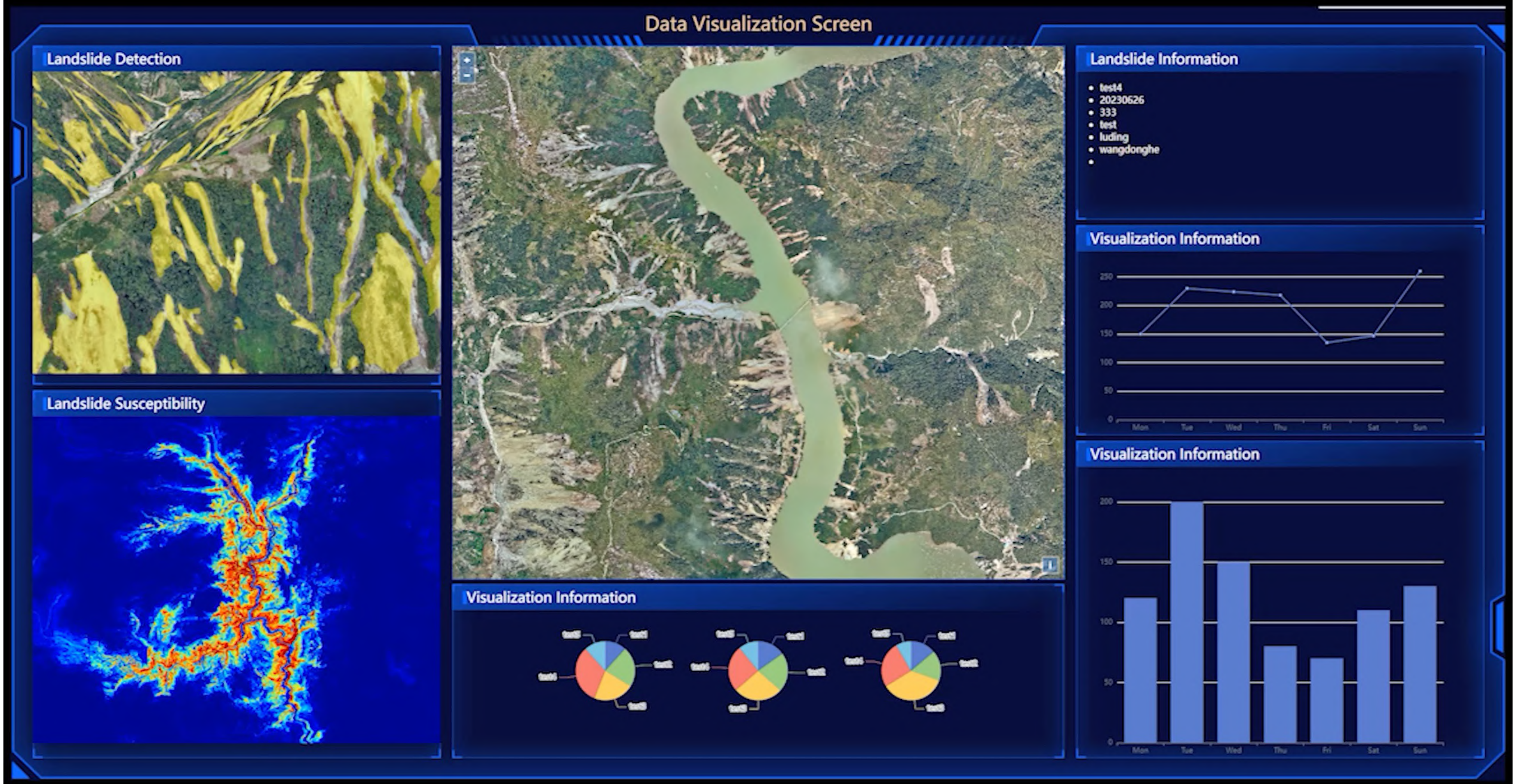


Dai LX, Fan XM * et al., *Landslides*, 2023

□ Prediction results were released 2 hours after the EQ



Accuracy 83.70%, Kappa coefficient is 0.54



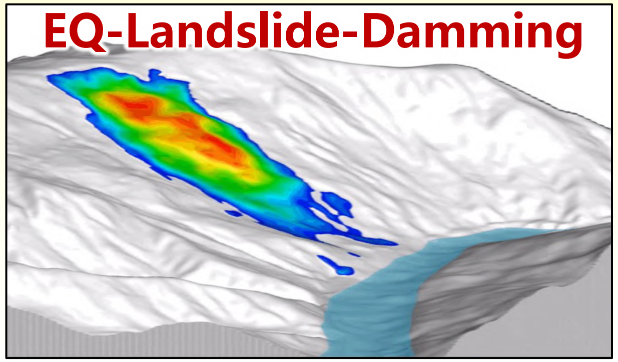
SESSION 6.4: Chengyong Fan, Xuanmei Fan, Xin Wang

Coseismic landslide dam and dam-breach flood prediction

Developed an integrated model for earthquake-induced landslide dam and dam-breach flood hazard chain evaluation

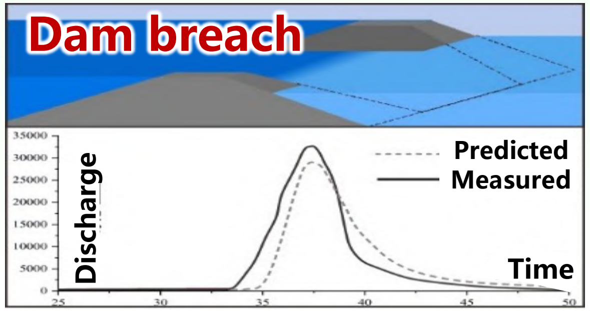
Landslide and dam formation simulation

- Slope seismic response
- EQ-triggered landslides
- Landslide dam formation simulation



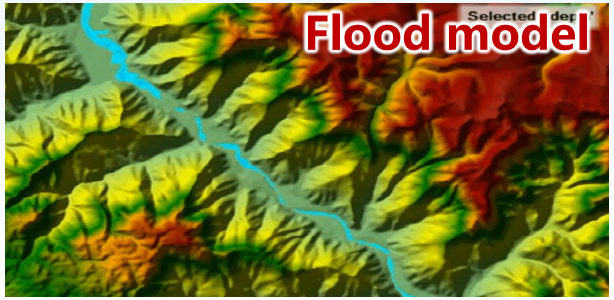
Dam breach based on fluid-solid coupling

- Reservoir volume
- Breach time
- Dam-breach process
- Hydrograph

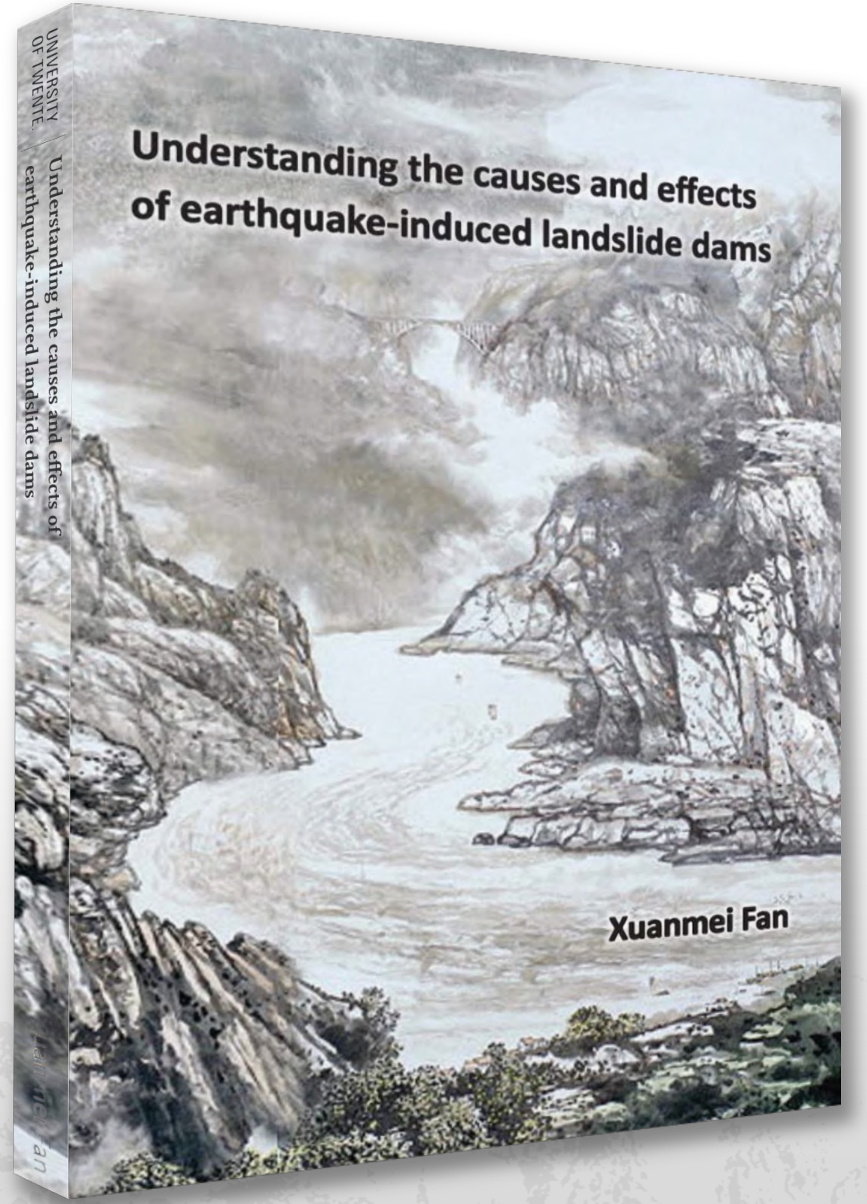


Dam breach flood simulation

- Downstream riverbed morphology based on GIS
- 1D/2D non-constant flow hydraulic model
- Flood parameters (Area/ depth/velocity…)

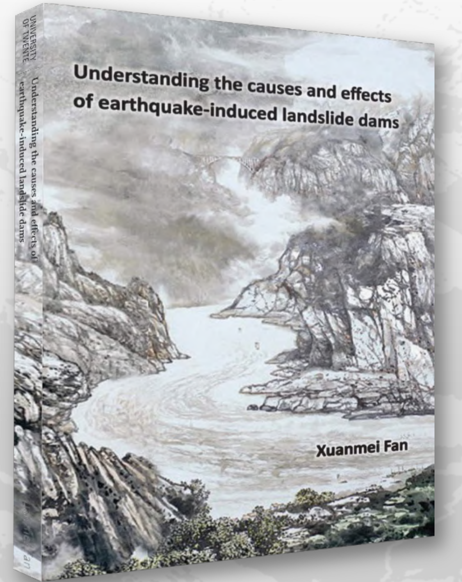


Fan XM et al., 2021a,b; 2013; Fan XM et al., *Earth Science Reviews*, 2020 and 2021




Earth-Science Reviews
Invited review
The formation and impact of landslide dams – State of the art
Xuanmei Fan, Anja Dufresne, Srikrishnan Siva Subramanian, Alexander Strom, Reginald Hermanns, Carlo Tacconi Stefanelli, Kenneth Hewitt, Ali P. Yunus, Stuart Dunning, Lucia Capra, Marten Geertsema, Brendan Miller, Nicola Casagli, John D. Jansen, Qiang Xu


Earth-Science Reviews
Recent technological and methodological advances for the investigation of landslide dams
Xuanmei Fan, Anja Dufresne, Jim Whiteley, Ali P. Yunus, Srikrishnan Siva Subramanian, Chukwueloka A.U. Okeke, Tomáš Pánek, Reginald L. Hermanns, Peng Ming, Alexander Strom, Hans-Balder Havenith, Stuart Dunning, Gonghui Wang, Carlo Tacconi Stefanelli



Earth-Science Reviews 203 (2020) 103116

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

The formation and impact of landslide dams – State of the art

Xuanmei Fan[a], Anja Dufresne[b,*], Srikrishnan Siva Subramanian[a,*], Alexander Strom[c], Reginald Hermanns[d,e], Carlo Tacconi Stefanelli[f], Kenneth Hewitt[g], Ali P. Yunus[a], Stuart Dunning[h], Lucia Capra[i], Marten Geertsema[j], Brendan Miller[j], Nicola Casagli[f], John D. Jansen[a,k], Qiang Xu[a]

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ARTICLE INFO

Keywords:
landslide dam
worldwide database
classification
stability
geomorphological impacts
landscape evolution

ABSTRACT

The blocking of river courses by mass movements is very common in mountainous areas with deep and narrow valleys. Landslide dams may pose serious threats to people and their livelihoods downstream in the case of abrupt dam failure. Since the publication of benchmark reviews of Costa and Schuster (1988) and Korup (2002), there is a growing number of studies focusing on the formation, stability, and short-term impacts of landslide dams. This review combines the insights of all these studies, builds on current concepts of landslide dams, and suggests ways to unify terminologies and classifications. We furthermore present a new worldwide database compiled from literature data. It contains 410 landslide dams > 1 million m^3 in volume that were formed since 1900 since these have the most complete data entries. These data show that dam longevity is, among other factors, correlated with the type of landslide forming the dam. Those formed by rock/debris avalanches and rockslides have longest lifespans. However, the influence of landslide type or material on dam longevity decreases with time after dam formation. To ensure consistency in the next database generation, we suggest guidelines for data collection to provide a solid basis for evaluating dam stability and governing factors. A preliminary classification matrix for landslide dam stability that combines topographic setting and the internal structure of the dam body is another outcome of our review. Furthermore, an evaluation of the various geomorphic stability indices proposed in the literature regarding their suitability and limitations in assessing dam formation and stability shows that they predict the probability of dam formation reasonably well, but that their application to longevity estimates requires further assessment. The geomorphic impacts of landslide dams in the short-, medium- and long term are summarized and illustrated with key examples. Finally, for a better understanding of the factors controlling dam stability, we recommend to (1) include dam composition and sedimentary structures in future case studies, (2) maintain and update the worldwide database for sound statistical analyses, (3) refine landslide dam stability indices and test them for different landslide types, and (4) study hazard cascades related to multiple dams in one watershed. For long-term landscape evolution studies, we suggest to (5) quantify terrestrial sediment flux related to landslide dams, (6) detect ancient landslide dams in river profiles, and (7) further exploit the sediment archives in former impoundment areas.

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Recent technological and methodological advances for the investigation of landslide dams

Xuanmei Fan[a], Anja Dufresne[b,*], Jim Whiteley[c,d], Ali P. Yunus[a], Srikrishnan Siva Subramanian[a], Chukwueloka A.U. Okeke[e], Tomáš Pánek[f], Reginald L. Hermanns[g,h], Peng Ming[i], Alexander Strom[j], Hans-Balder Havenith[k], Stuart Dunning[l], Gonghui Wang[m], Carlo Tacconi Stefanelli[n]

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ARTICLE INFO

Keywords:
Landslide dam
Sedimentology
Embankment dam
Hazard mitigation
Geophysics
Numerical modelling
Remote sensing
Dating
Rockslide dam

ABSTRACT

River-damming by landslides is a widespread phenomenon around the world. Recent advances in remote sensing technology and the rising commercial availability of their products enable the assemblage of increasingly more complete inventories and improve monitoring efforts. On the ground, multi-method dating campaigns enhance our understanding of the timelines of dam formation and failure. In comparison to single-dating methods, they reduce uncertainty by using different materials from the landslide deposit, facilitate the advantages of each method, and consider the deposit and the source area. They can pin dates on the time of lake drainage where backwater sediments are included in the dating campaign and thus inform about dam longevity. Geophysical methods provide non-invasive and rapid methods to investigate the properties and interior conditions of landslide dams. By identifying, e.g. evolving zones of weakness and saturation they can aid in the monitoring of a dam in addition to providing information on interior stratification for scientific research. To verify results from geophysical campaigns, and to add details of dam interior structures and geotechnical properties, knowledge of their sedimentology is essential. This information is gathered at sections from breached dams, other (partially) eroded landslide deposits, and through laboratory testing of sampled material. Combining the knowledge gained from all these methods with insights from blast-fill and embankment dam construction, physical and numerical modelling in multi-disciplinary research projects is the way forward in landslide dam research, assessment and monitoring. This review offers a broad, yet concise overview of the state-of-the-art in the aforementioned research fields. It completes the review of Fan et al. (2020) on the formation and impact on landslide dams.

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Post-seismic hazard evolution and prediction

SKL
国家重点实验室
STATE KEY LABORATORY

Challenges：

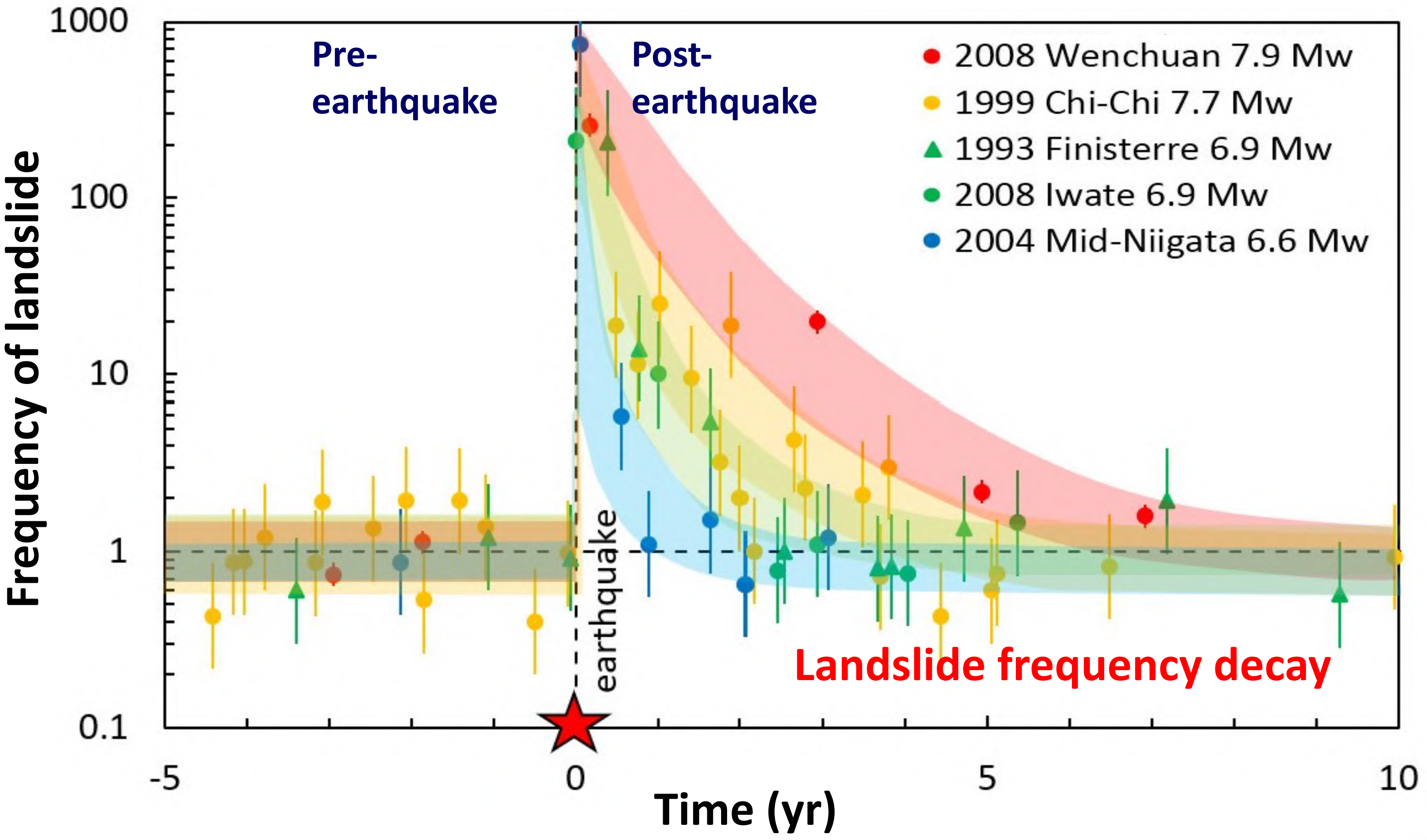
How do post-earthquake landslides and debris flows evolve?

What are the mechanisms and how to simulate?

The Wenjia debris flow after the Wenchuan earthquake

Evolution of post-seismic landslide in time

Evolution of Landslides Over Time After Strong Earthquakes Worldwide

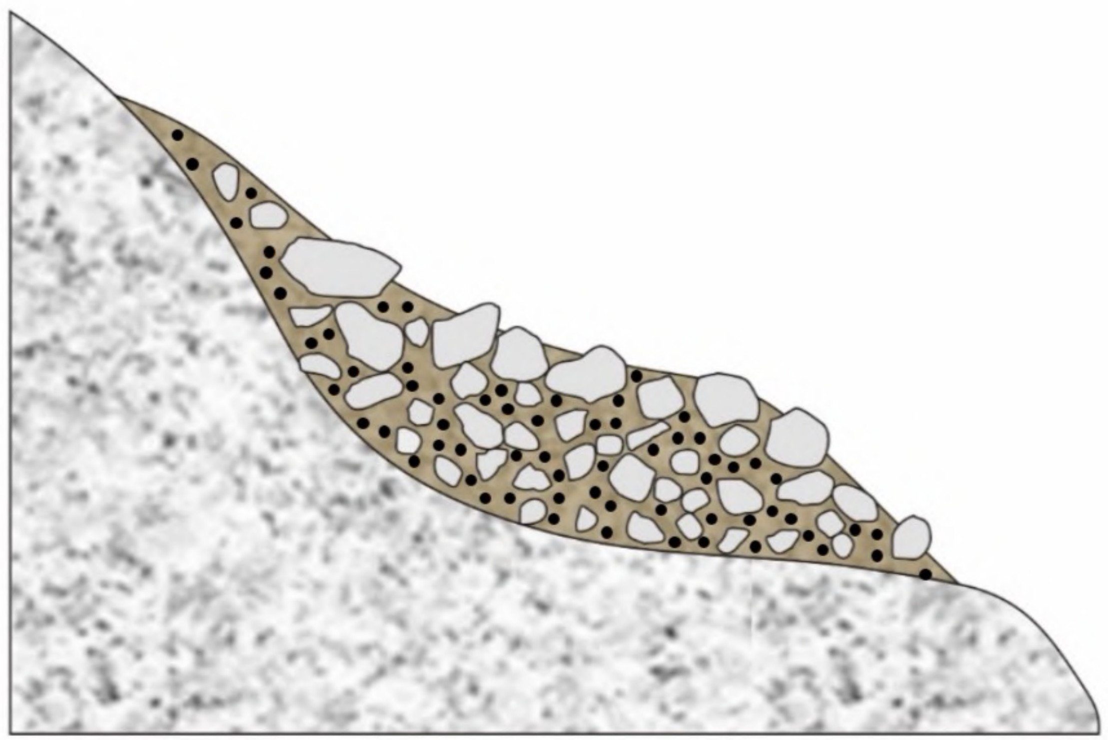


- The frequency of landslides increases significantly after earthquakes and then **decays within a decade following a power-law** to the pre-earthquake level

Fan XM* et al, *Landslides*, 2018c
Fan XM et al., *Reviews of Geophysics*, 2019

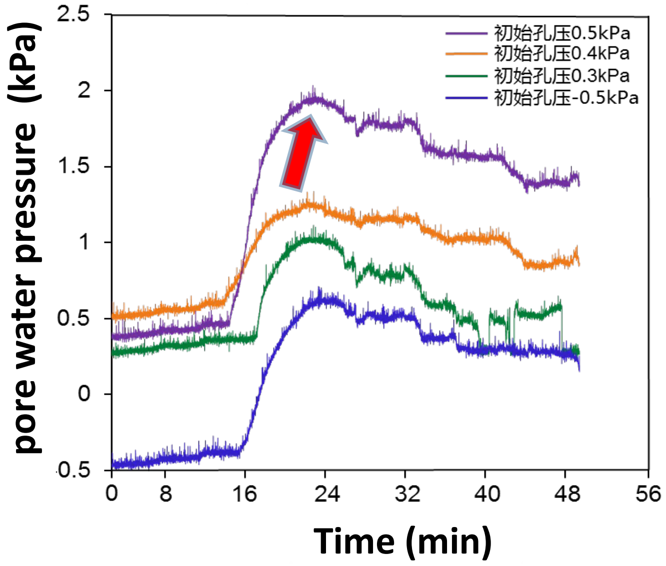
□ Mechanism of post-earthquake landslides and debris flows

Static liquefaction mechanism



Hydrodynamic force → fine particles migration → pore pressure increase → static liquefaction → slope instability

Pore water pressure surge slope instability



Grain coarsening

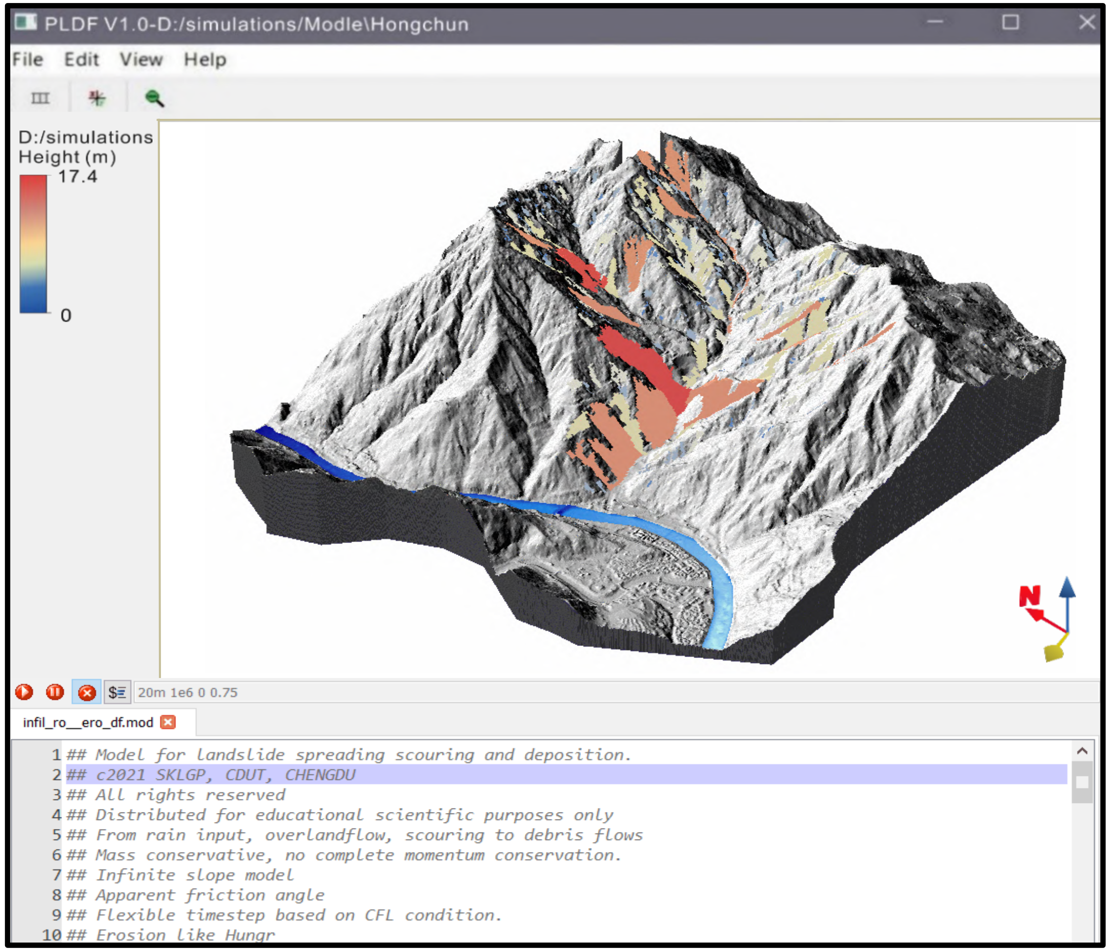
Fan XM et al., *Engineering Geology*, 2018, 2023

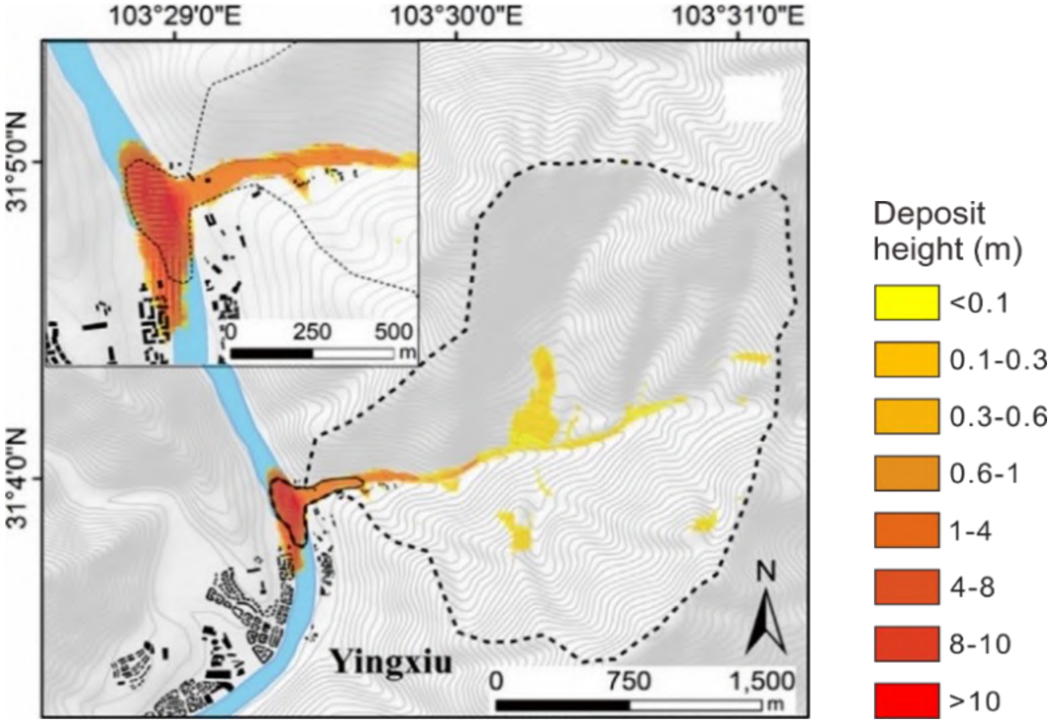
Prediction of post-seismic hazard chain

□ Developed a Numerical Model for Landslides-Debris Flows

Multi-hazard chain scenarios through an integrated numerical modelling approach:

Post-seismic landslides → debris flow → dammed river → outburst flood





Special thanks and memory of Prof. Theo van Asch

Domenech, Fan XM * et al., *Engineering Geology*, 2019

Yang, Fan XM* et al., *Engineering Geology*, 2023

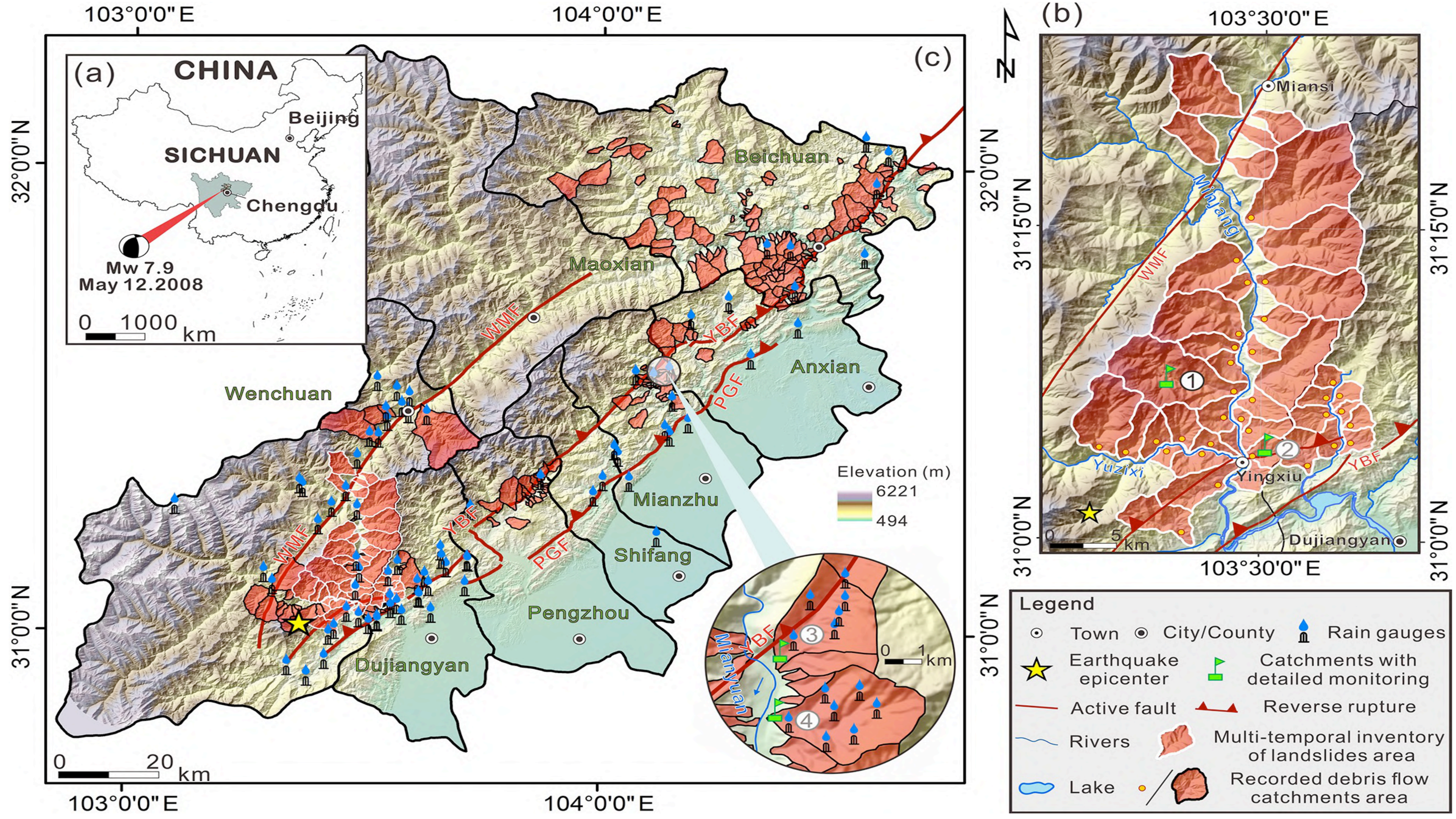
Challenges:

How to prevent and early warn post-earthquake debris flows?

Debris flows after the 2008 Wenchuan earthquake

☐ Images after the 20 August 2019 debris flow events

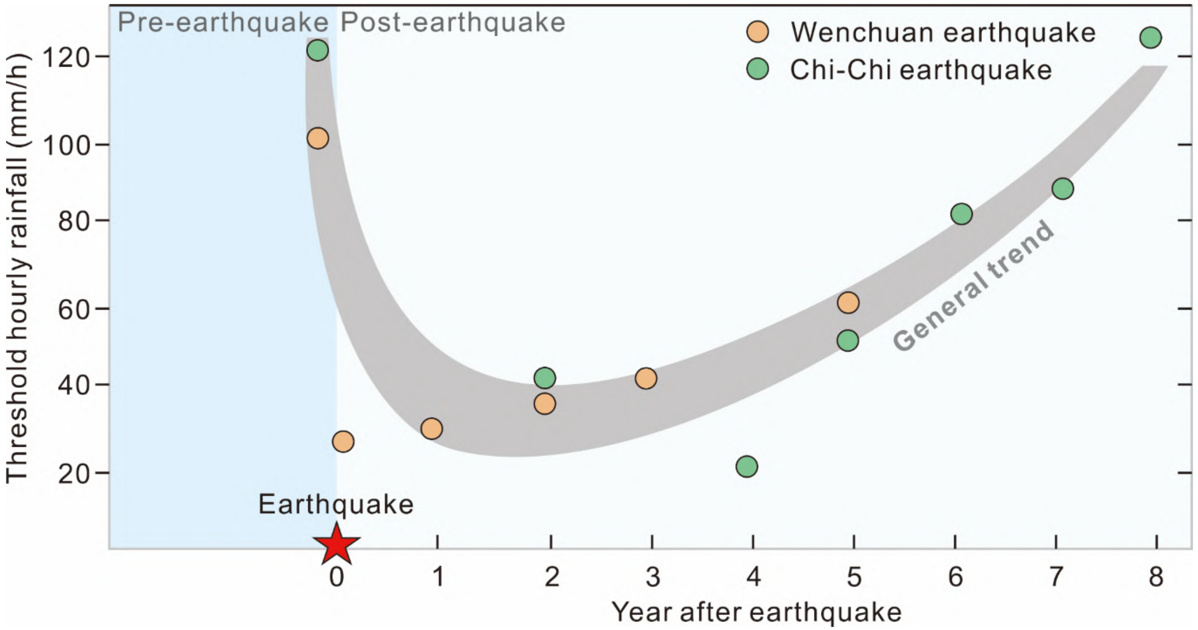
A database contains >500 post-earthquake debris flows



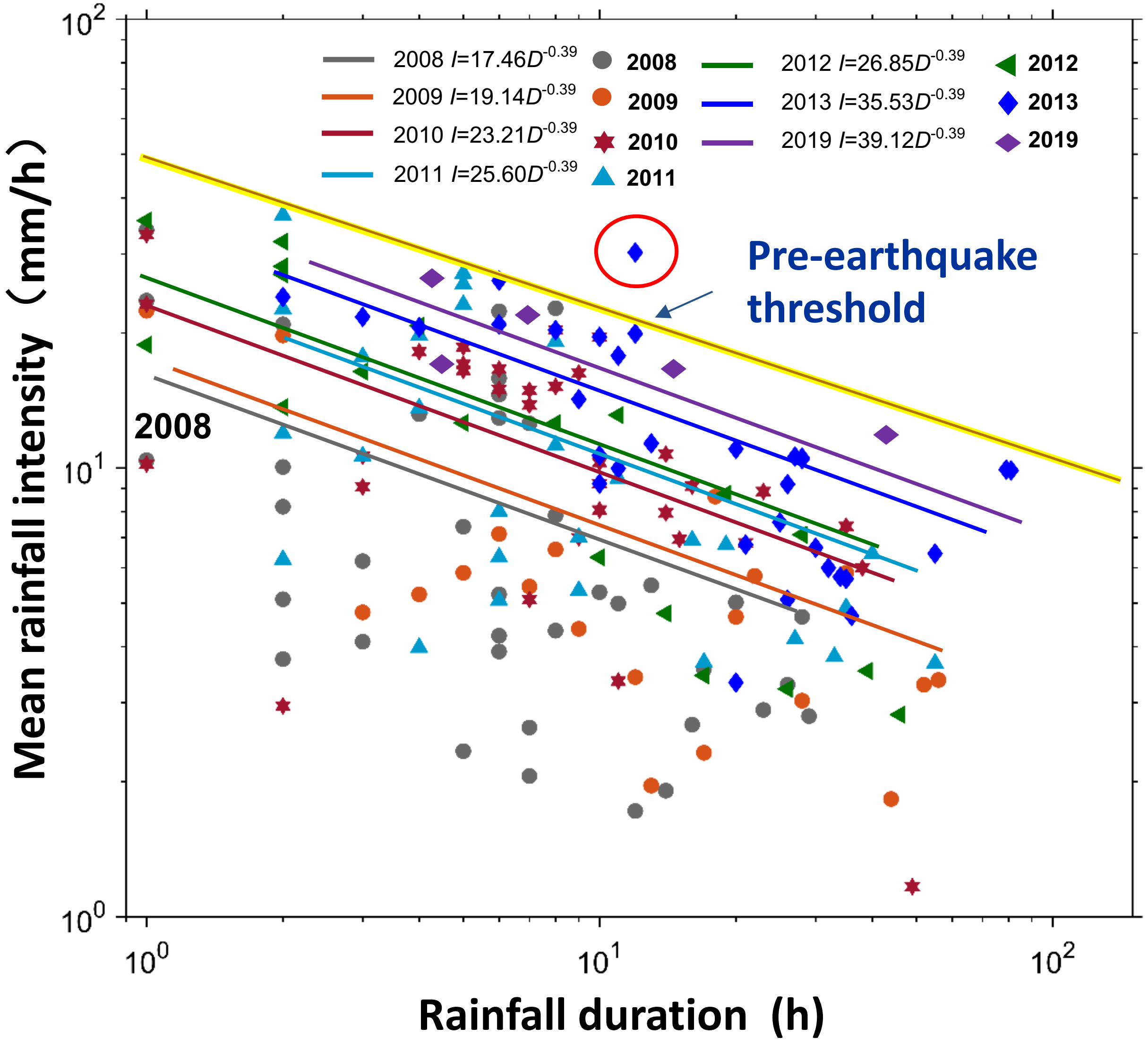
Fan * et al. *Earth Syst. Sci. Data*, 2019

Changing rainfall threshold of post-earthquake debris flows

☐ Evolution of rainfall threshold of debris flows after earthquake



The rainfall threshold of debris flows after earthquakes decreases to 1/3 of that before earthquake, and then increases gradually with time

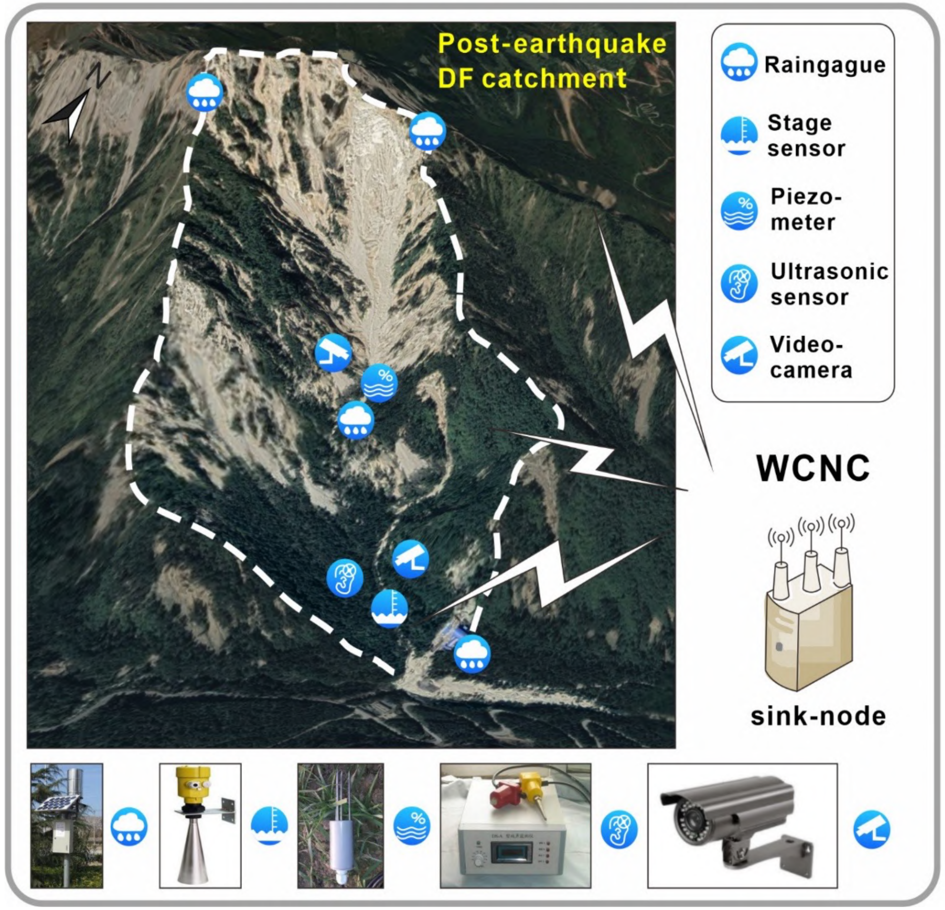


Jiang, Fan XM * et al., *Engineering Geology*, 2021

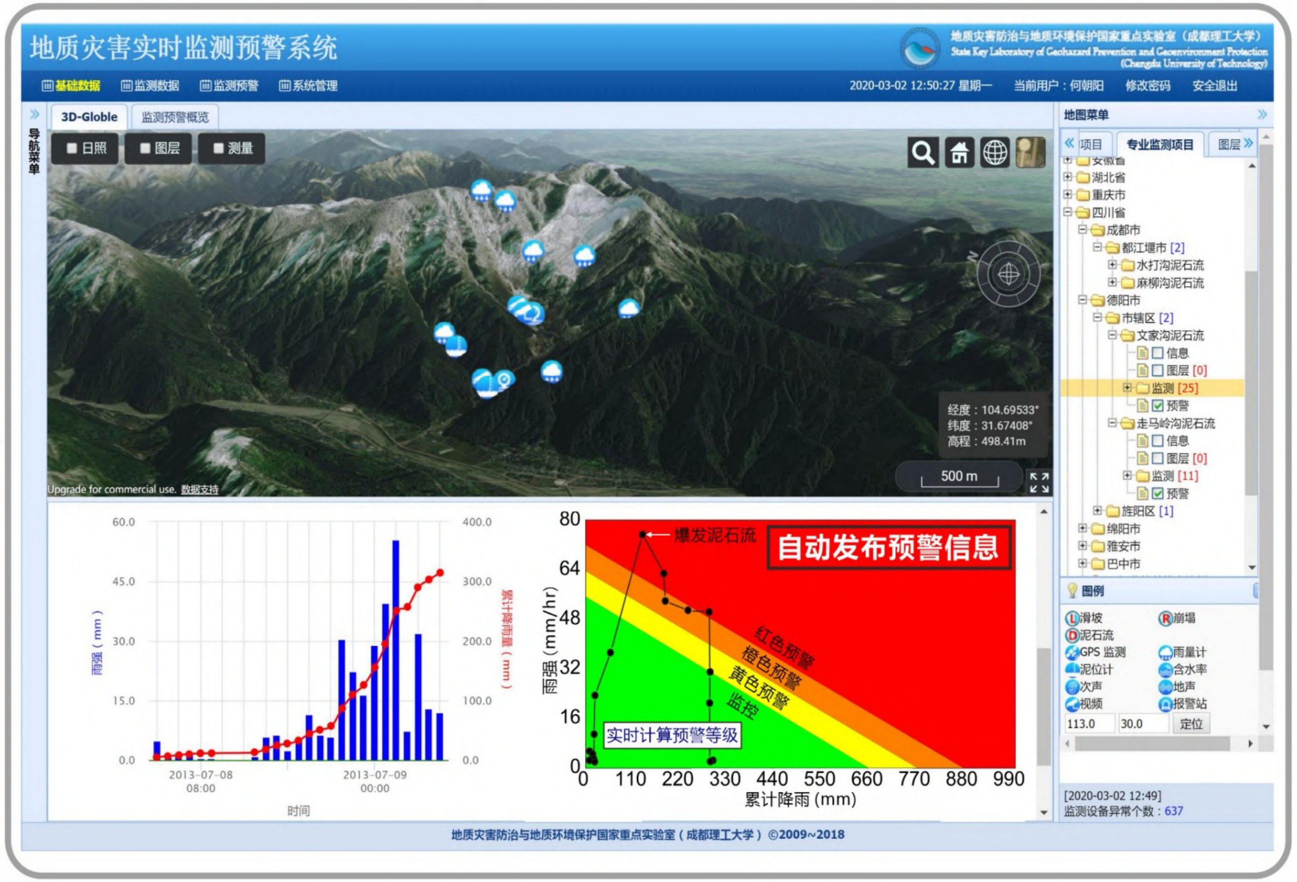
Early warning system of post-earthquake debris flows

◻ Real-time Early Warning System for Landslides and Debris Flows

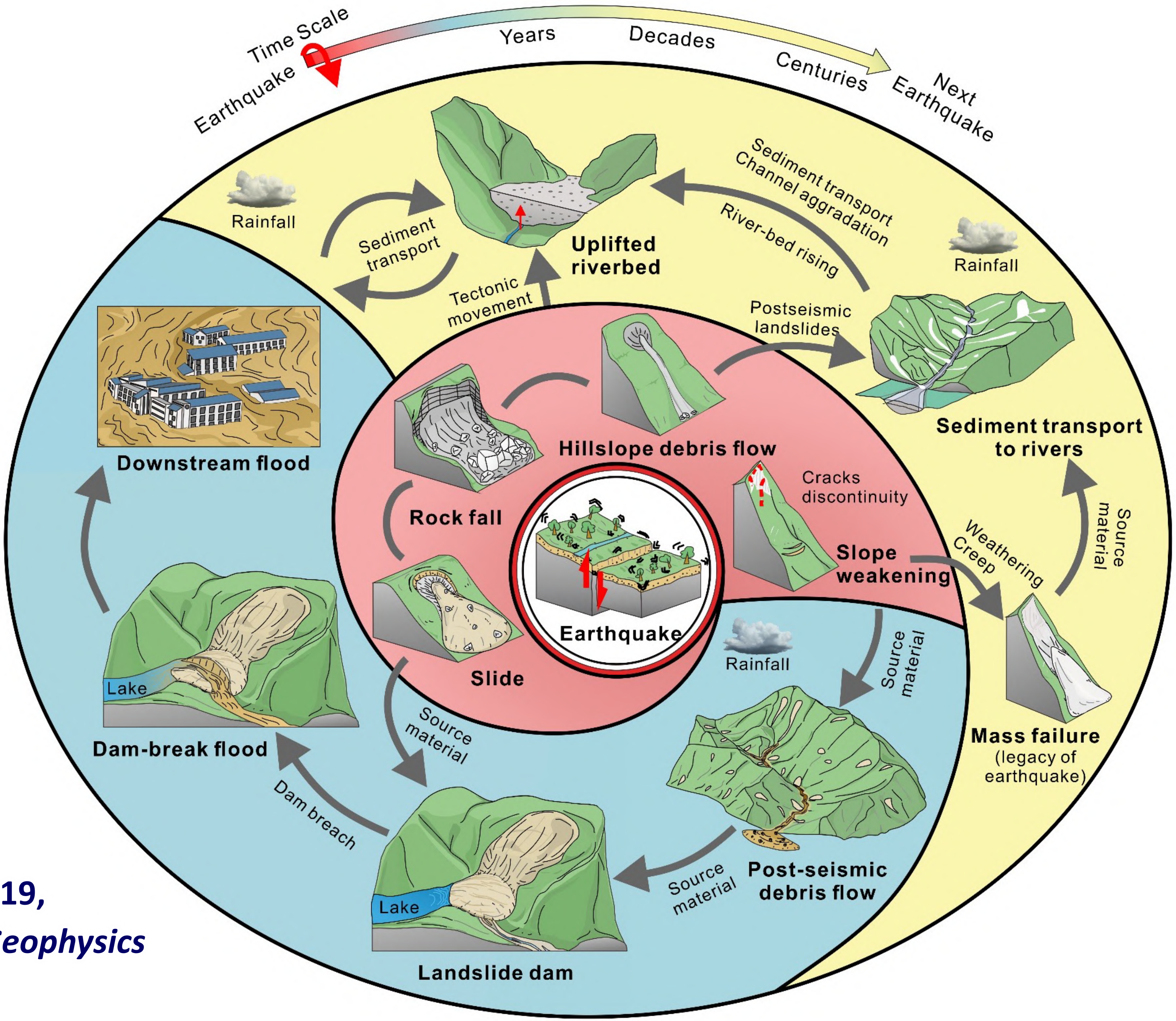
Debris-flow monitoring site

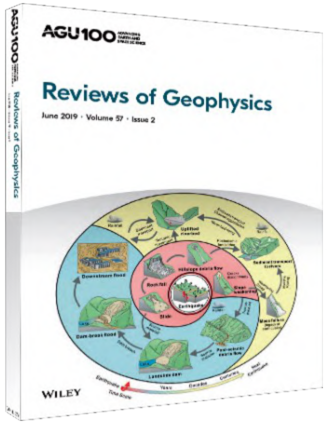


Real-time early warning system for landslides and debris flows



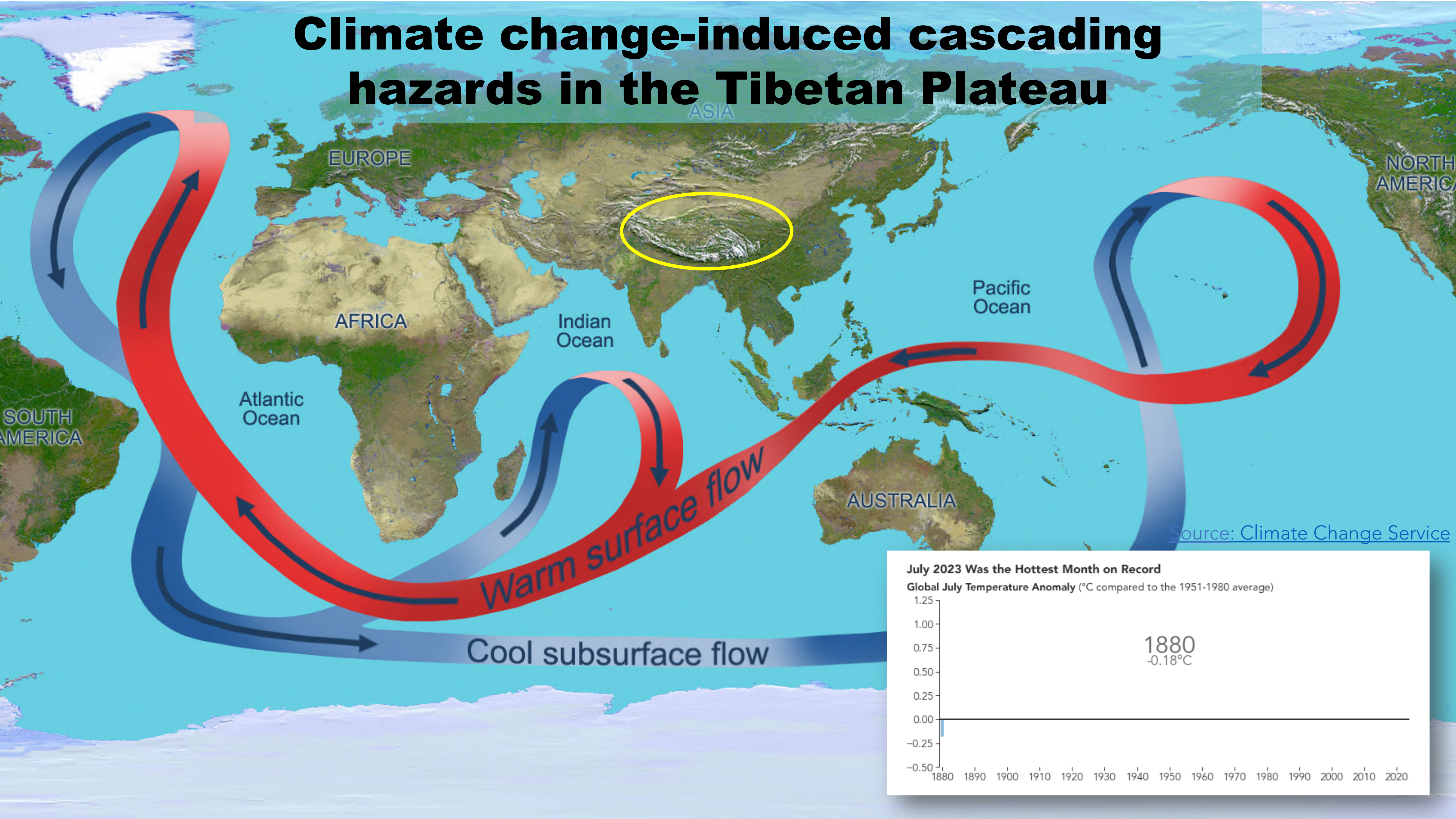
Successfully early warned more than 220 landslides and debris flows





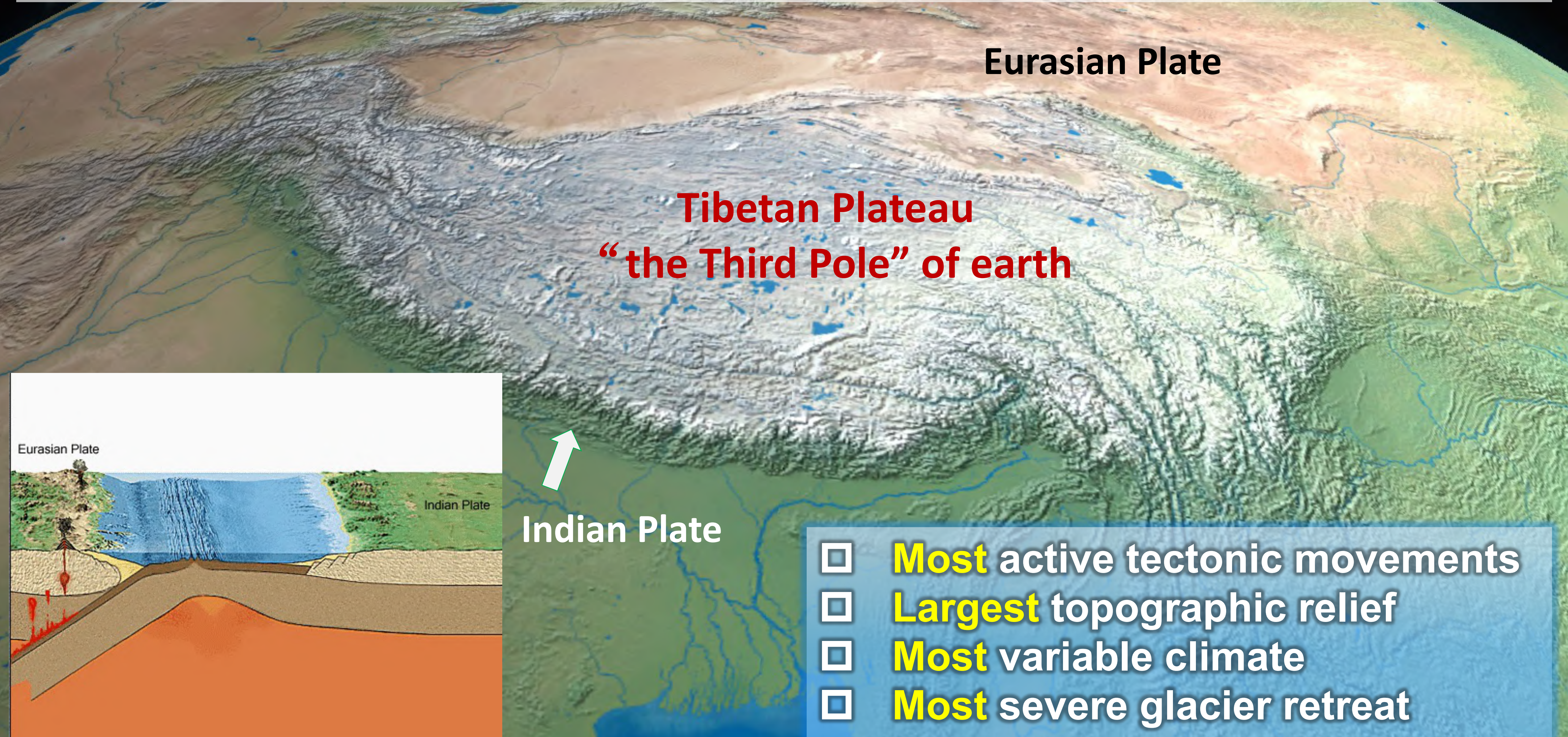
Fan et al., 2019,
Reviews of Geophysics

Climate change-induced cascading hazards in the Tibetan Plateau



Source: Climate Change Service

The Tibetan Plateau is one of the areas with the most complex geological conditions in the world, also called “the Third Pole” of earth.

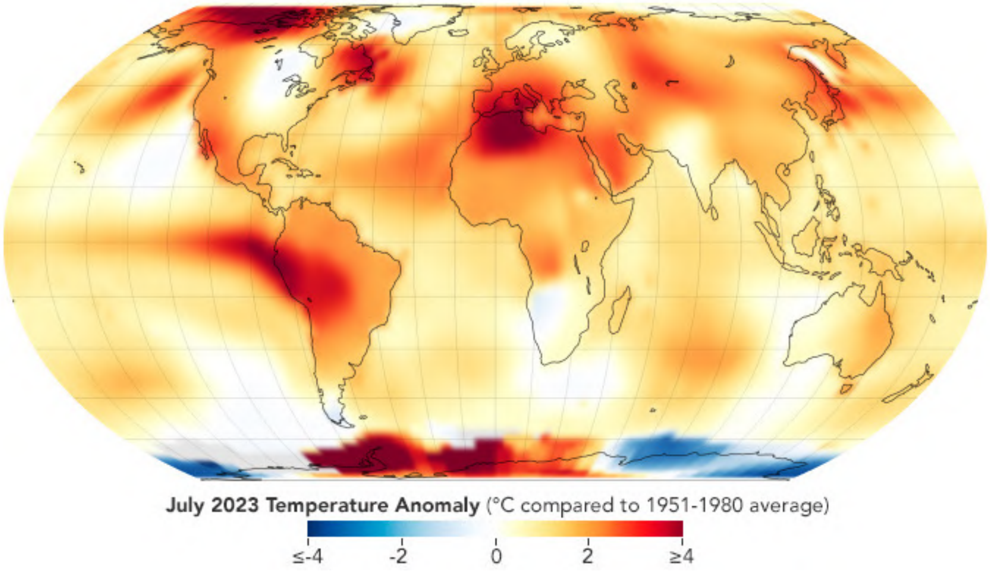


- ☐ **Most** active tectonic movements
- ☐ **Largest** topographic relief
- ☐ **Most** variable climate
- ☐ **Most** severe glacier retreat

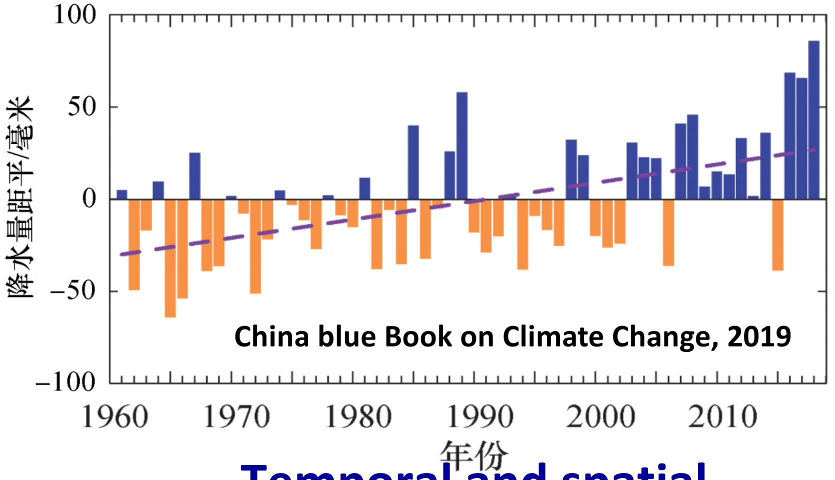
Observed climate and environmental changes in the Tibetan Plateau

TP is the region with the most intense climate change in the world: warming, wetting and greening

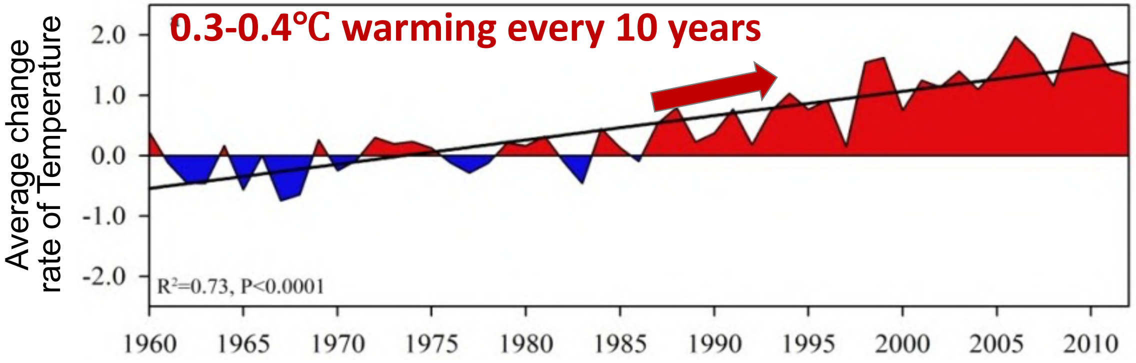
Global warming is unprecedented now



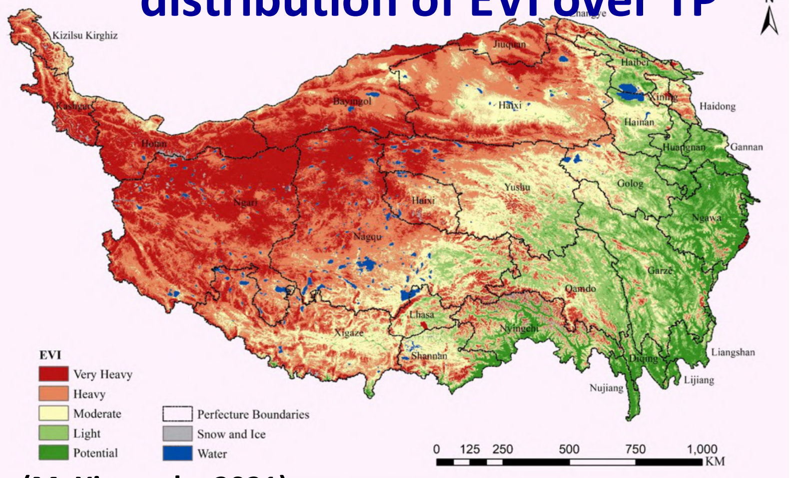
Changes of precipitation in TP since 1960



TP is warming twice as fast as the global average



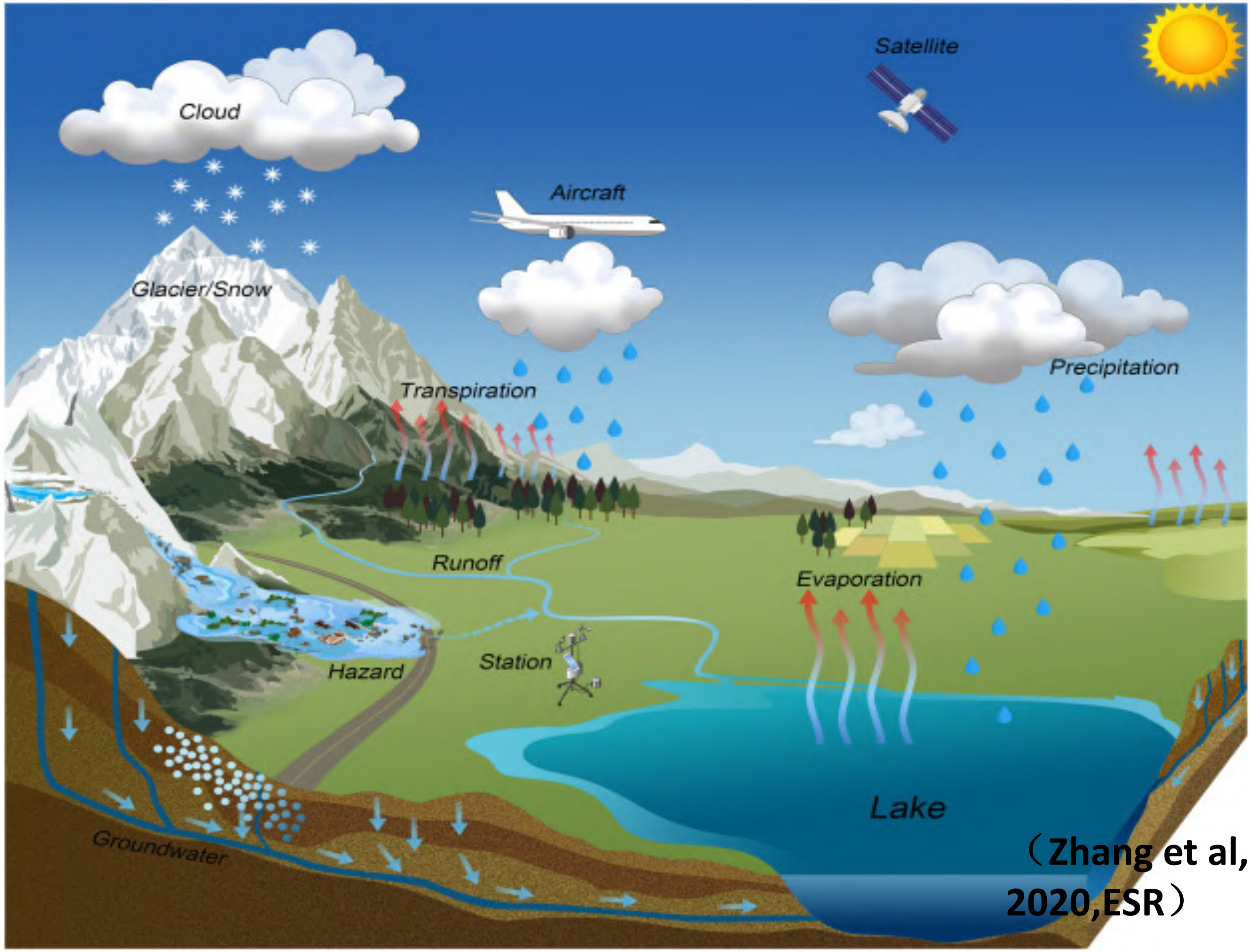
Temporal and spatial distribution of EVI over TP



(M. Xia et al. , 2021)

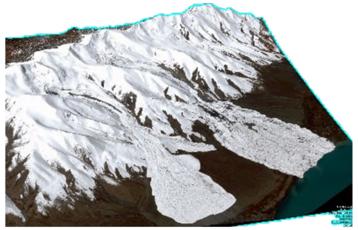
Global climate change enhances various types of geological hazards

With climate change, glaciers retreat, glacier lakes expand, which induced various types of geohazards in the Tibetan Plateau

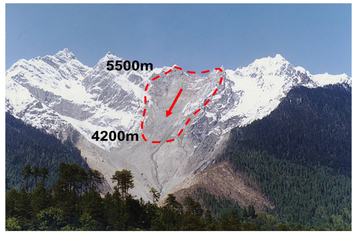


（Zhang et al, 2020,ESR）

Main hazard types



- Glacier collapses



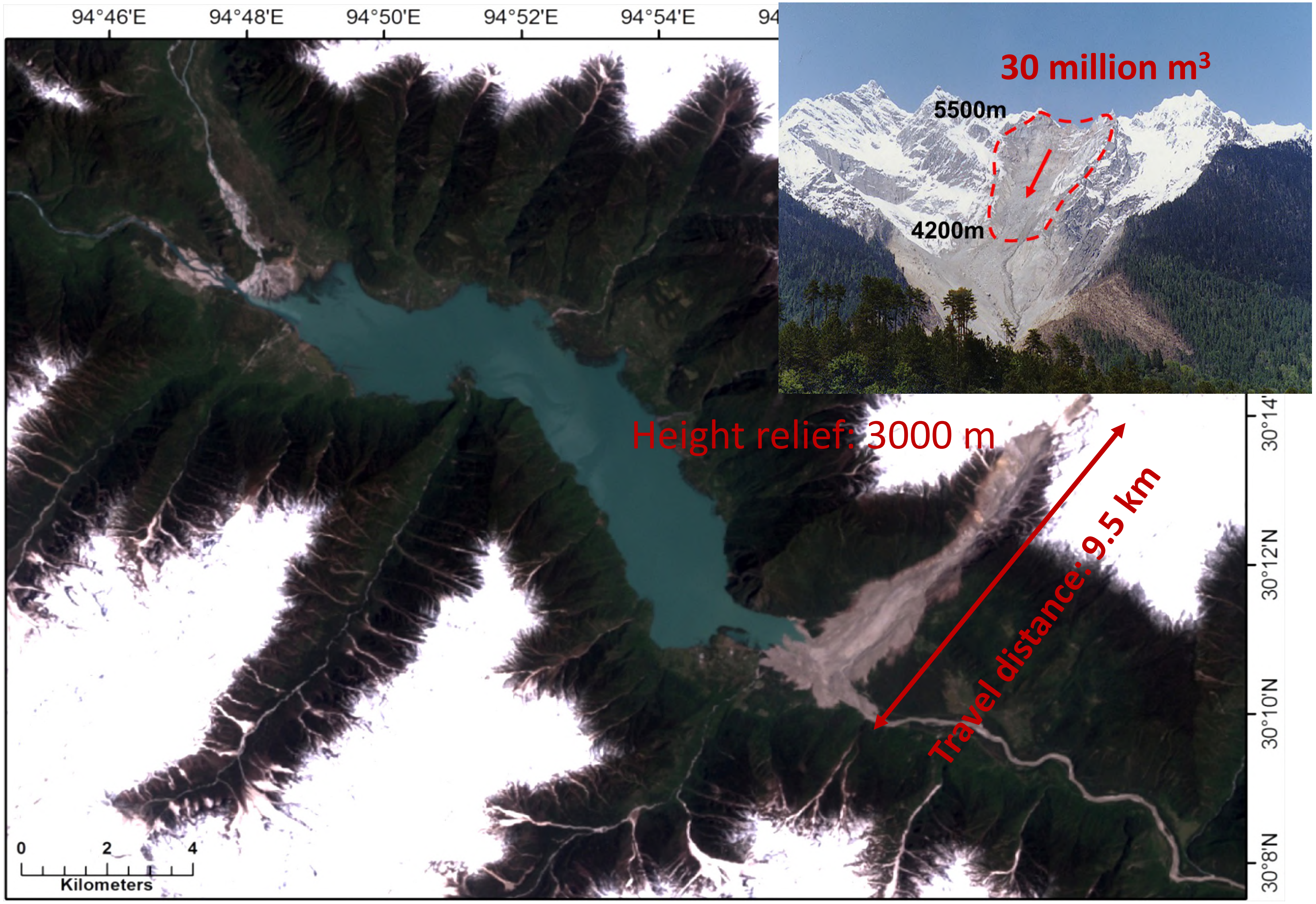
- Ice-rock avalanches

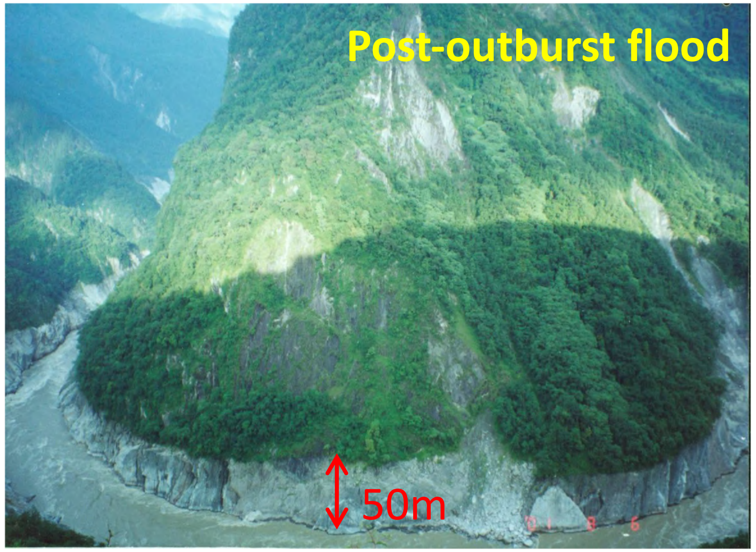
- Glacier lake outburst floods (GLOFs)

- Glacier-debris flows

Yigong landslide and dam-breach flood (4 April to 10 June, 2000)

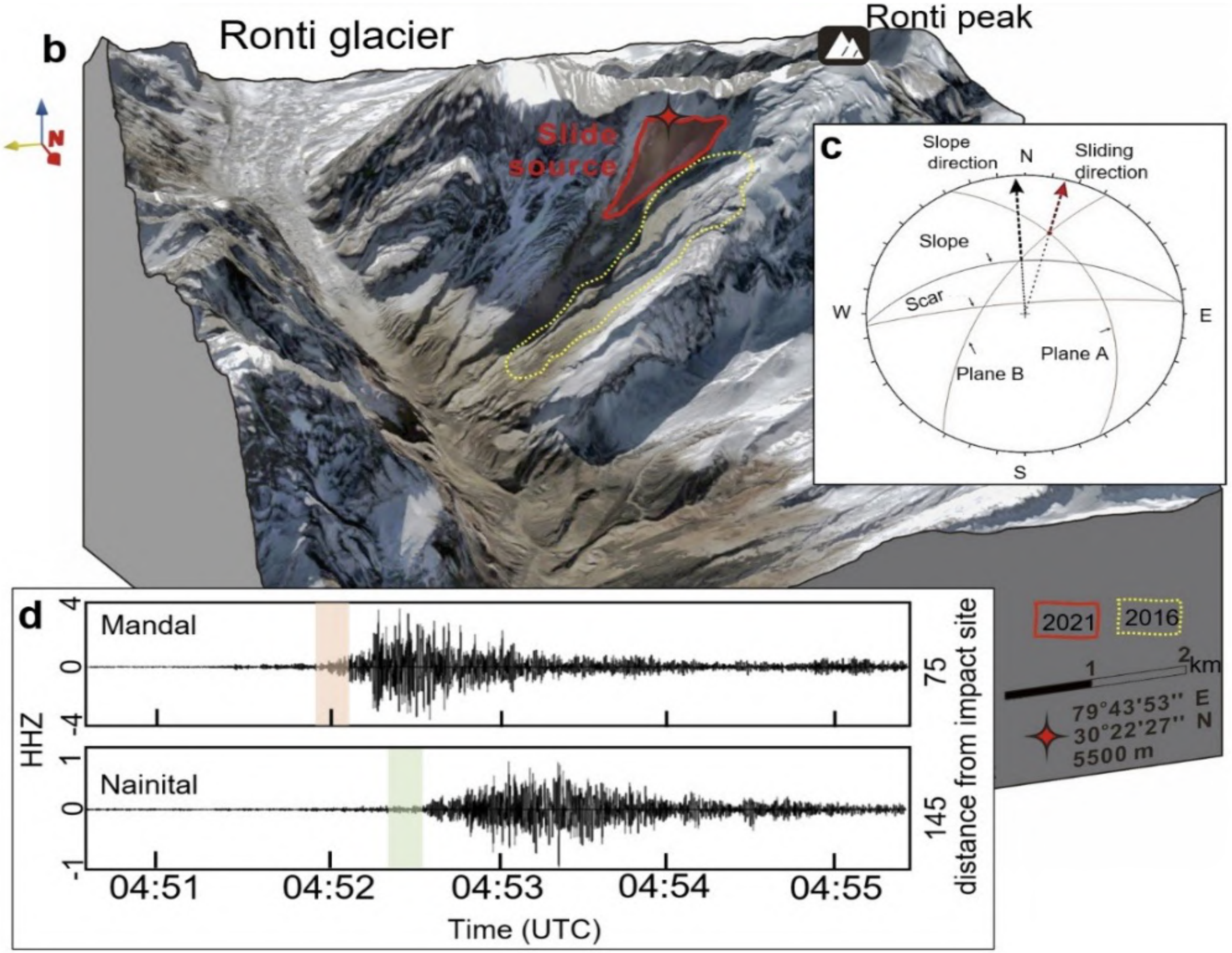
Cascading hazard: Rockslide→ Mass flow→ Damming river → Dam-breach flood





Indian Chamoli ice-rock avalanche (7 February, 2021)

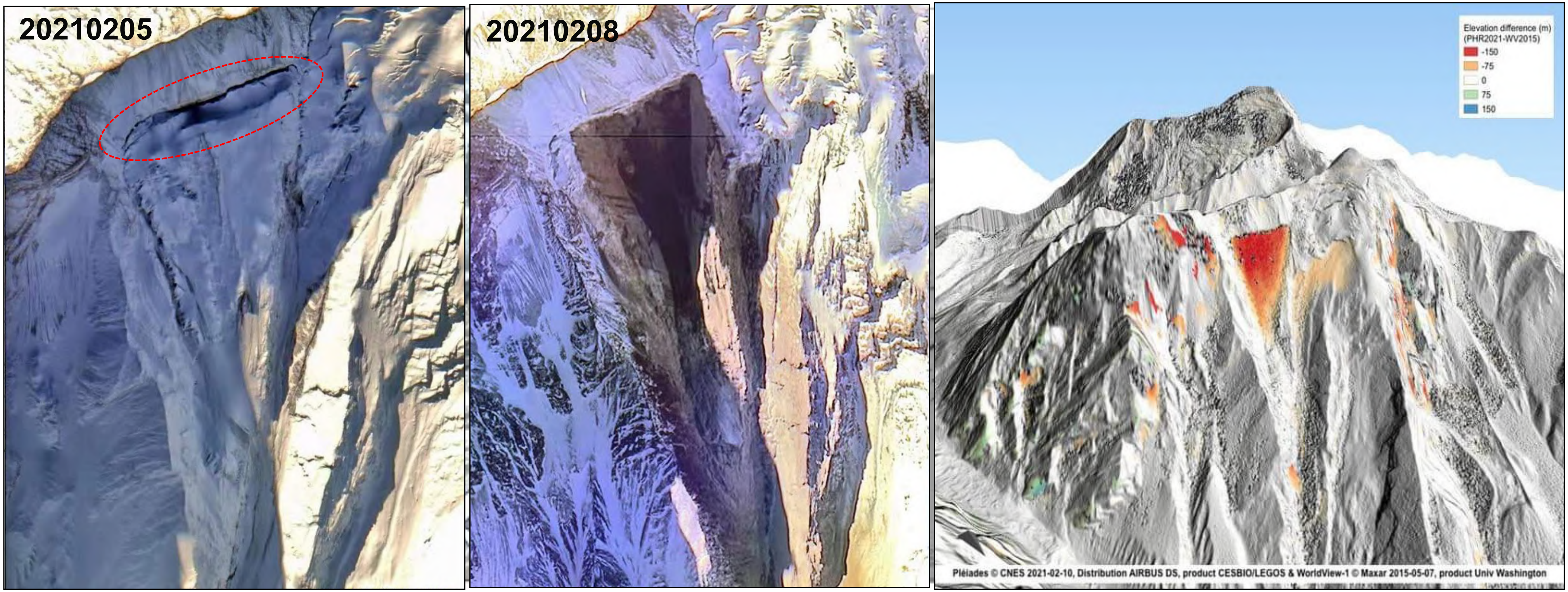
On February 7, 2021, a ice-rock avalanche occurred in the Chamoli area of northern India, which triggered flash floods, destroyed 2 hydropower stations, and killed >200 people



Fan et al. Science of Total Environment, 2022

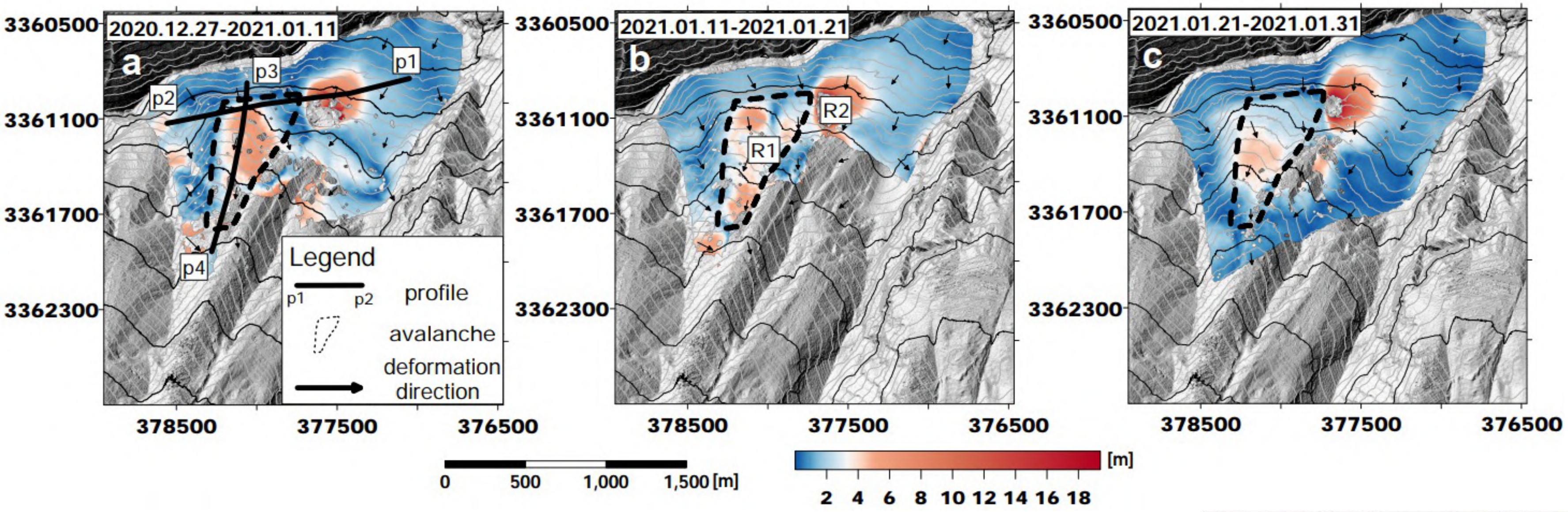
Indian Chamoli landslide (7 February, 2021)

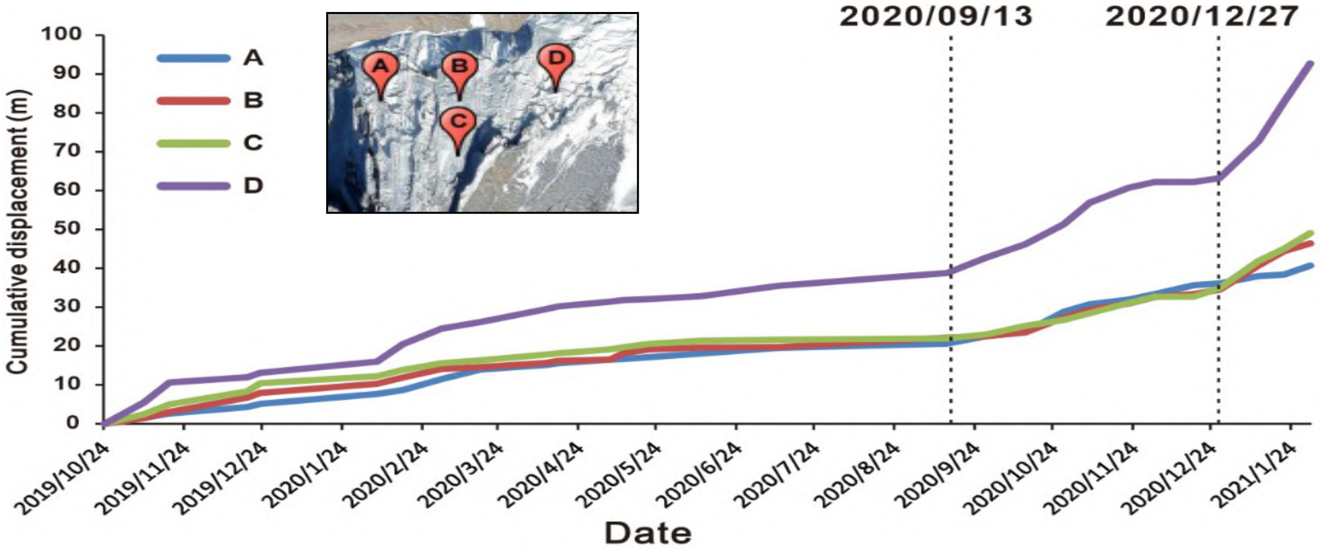
☐ The history of fracture expansion before the Chamoli rock-ice avalanche



Fan et al. Science of Total Environment, 2022

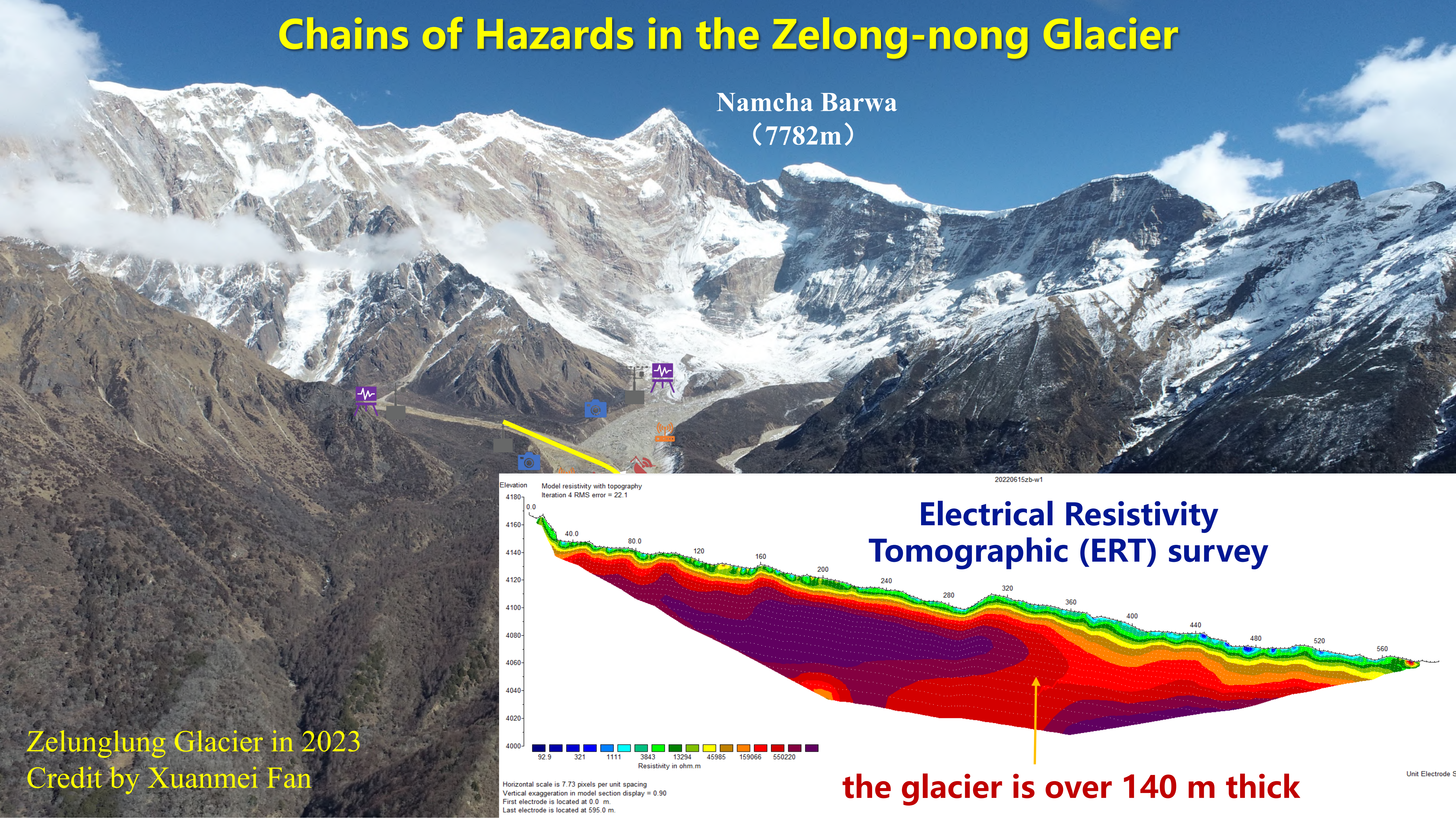
Indian Chamoli landslide (7 February, 2021)





Displacement curve

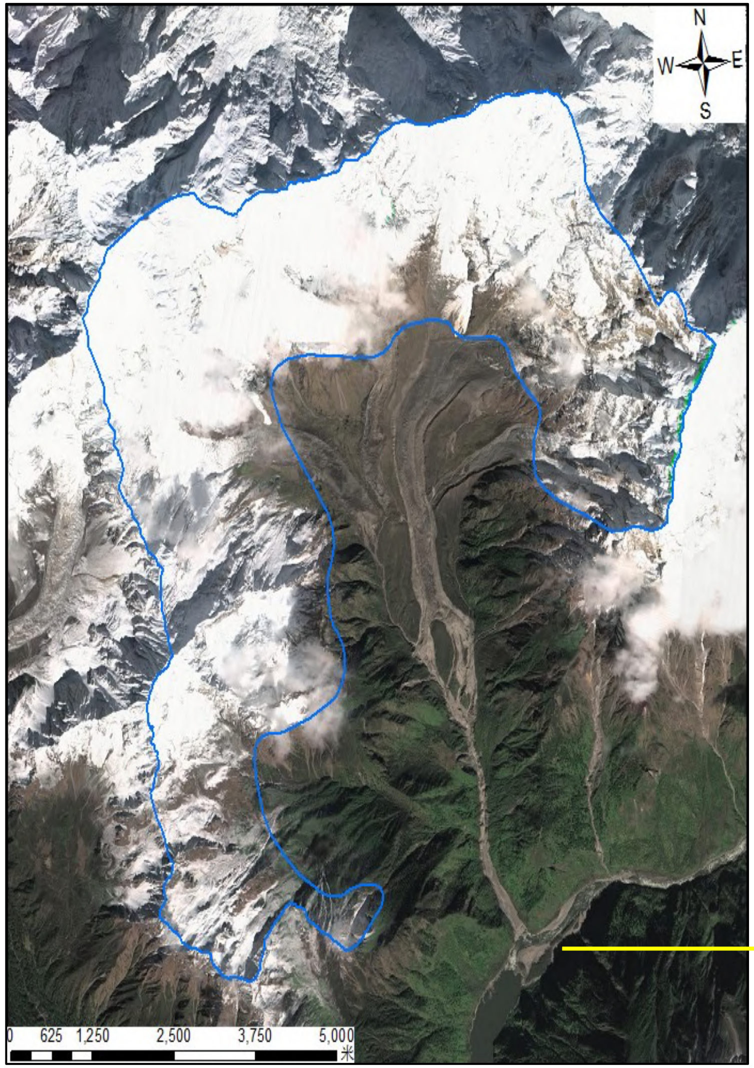
Typical Glacier-Related Hazards in Yarlung Tsangpo Grand Canyon



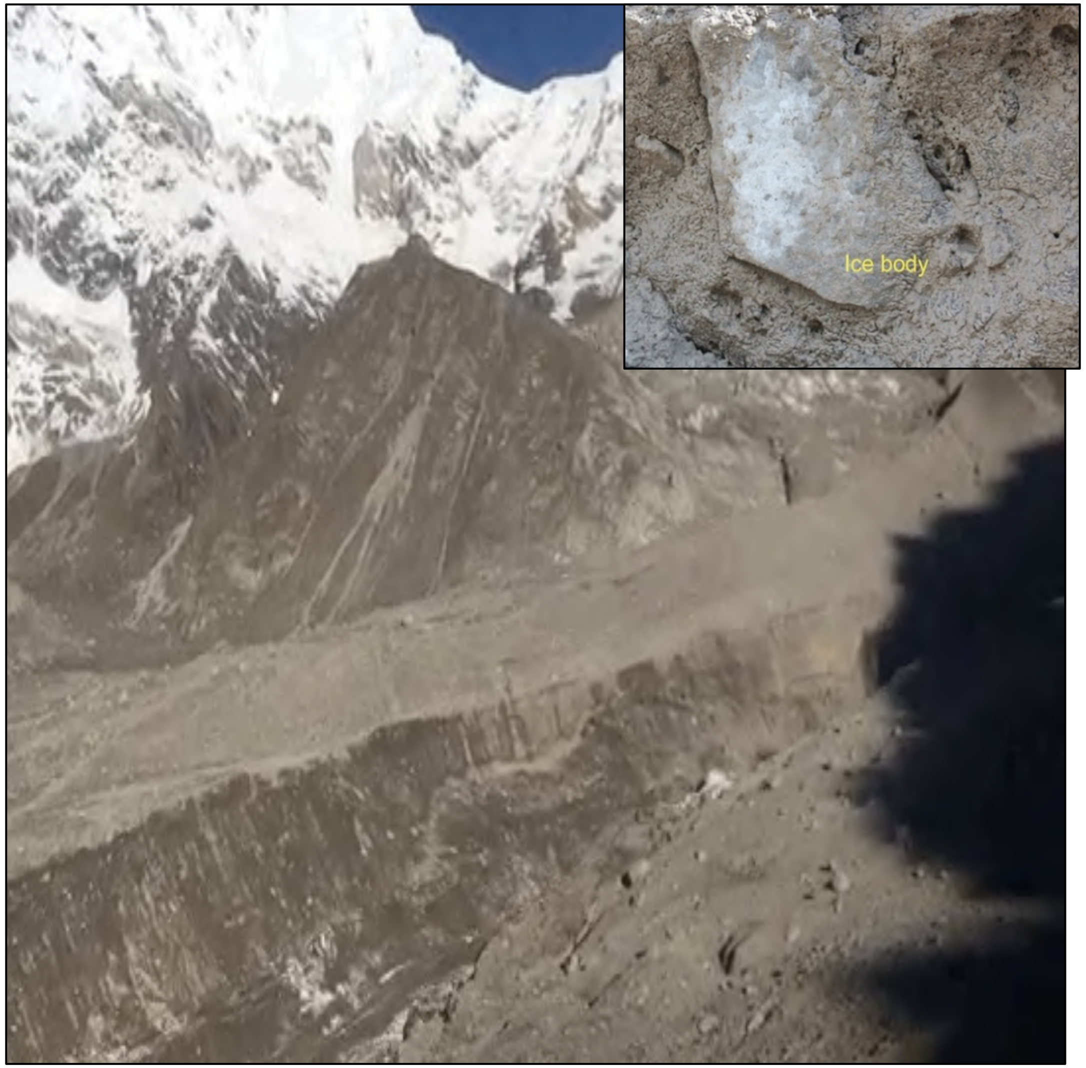
Chains of Hazards in the Zelong-nong Glacier
Namcha Barwa
（7782m）
Zelunglung Glacier in 2023
Credit by Xuanmei Fan
20220615zb-w1
Elevation
Model resistivity with topography
Iteration 4 RMS error = 22.1
Electrical Resistivity Tomographic (ERT) survey
4180
4160
4140
4120
4100
4080
4060
4040
4020
4000
0.0
40.0
80.0
120
160
200
240
280
320
360
400
440
480
520
560
92.9
321
1111
3843
13294
45985
159066
550220
Resistivity in ohm.m
the glacier is over 140 m thick
Horizontal scale is 7.73 pixels per unit spacing
Vertical exaggeration in model section display = 0.90
First electrode is located at 0.0 m.
Last electrode is located at 595.0 m.

Catastrophic chains of geohazard events in the Sedongpu catchment

Cascading hazard: Ice/Rock avalanches → Debris flow→ Damming →Dam-breach flood

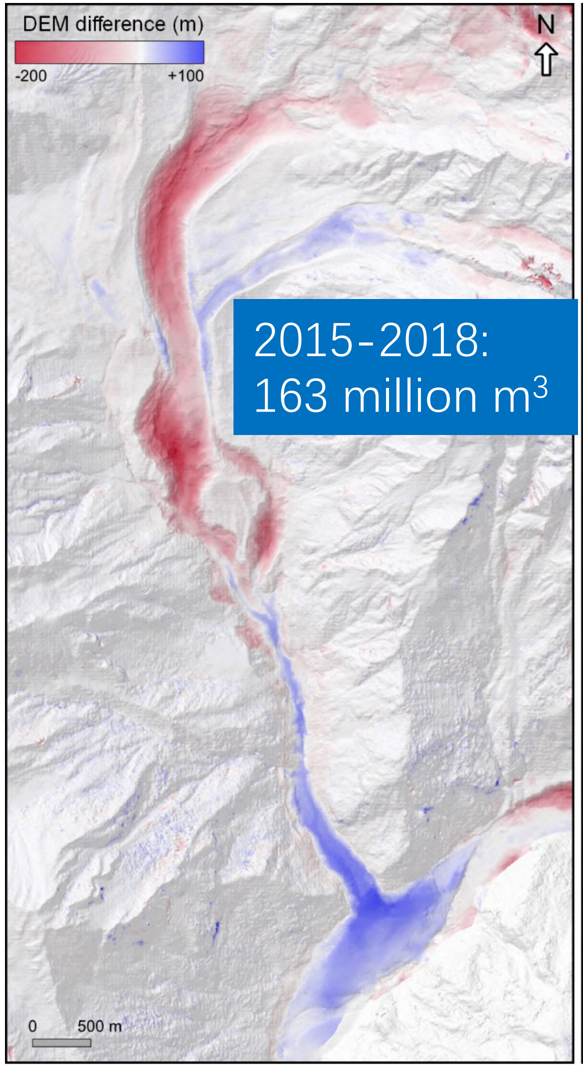


Past damming events
1973.3-1974.11
1975.12-1979.4
2014.6.1~2014.8.23
2017.10.22
2017.12.21
2018.10.16
2018.10.29
2021.3.22
2023.09.28
2023.10.03

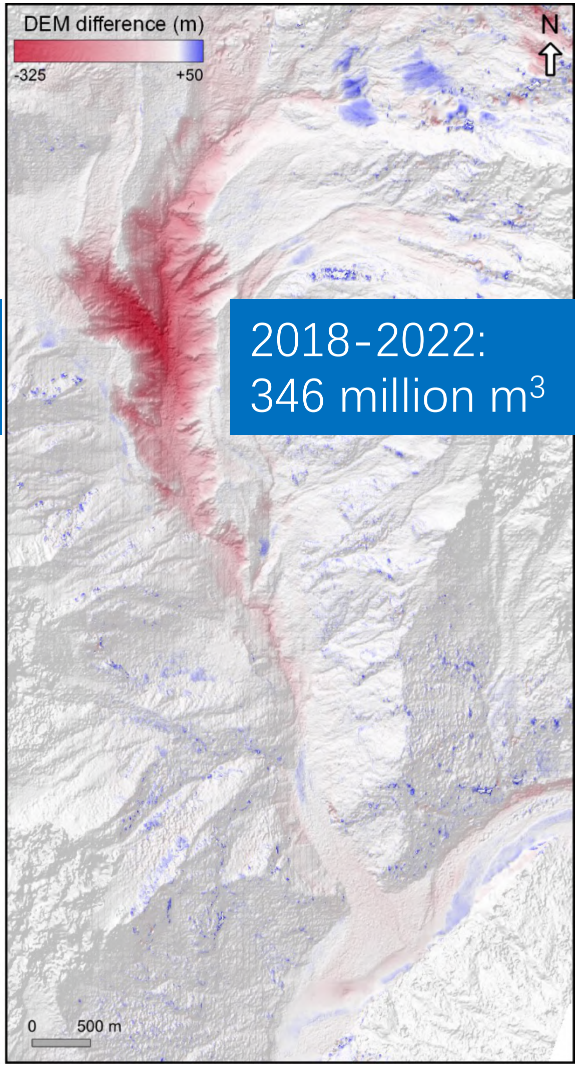


Highest erosion rate due to debris flow in Sedongpu Gulley

Frequent debris flow eroded about 500 million m^3 of deposits between 2015-2022



2015-2018:
163 million m^3

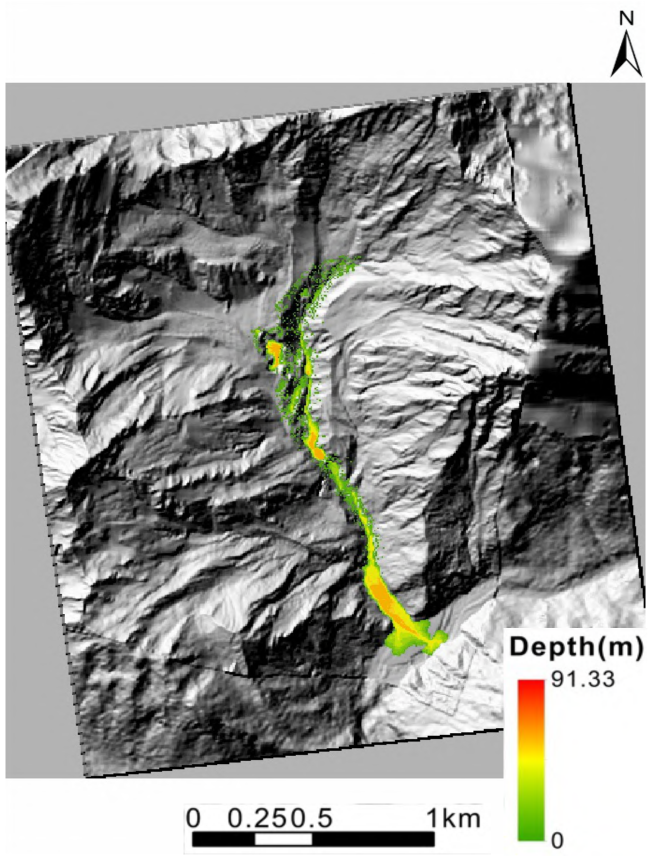


2018-2022:
346 million m^3

DDA-DF model: Scenario-based prediction of future hazard

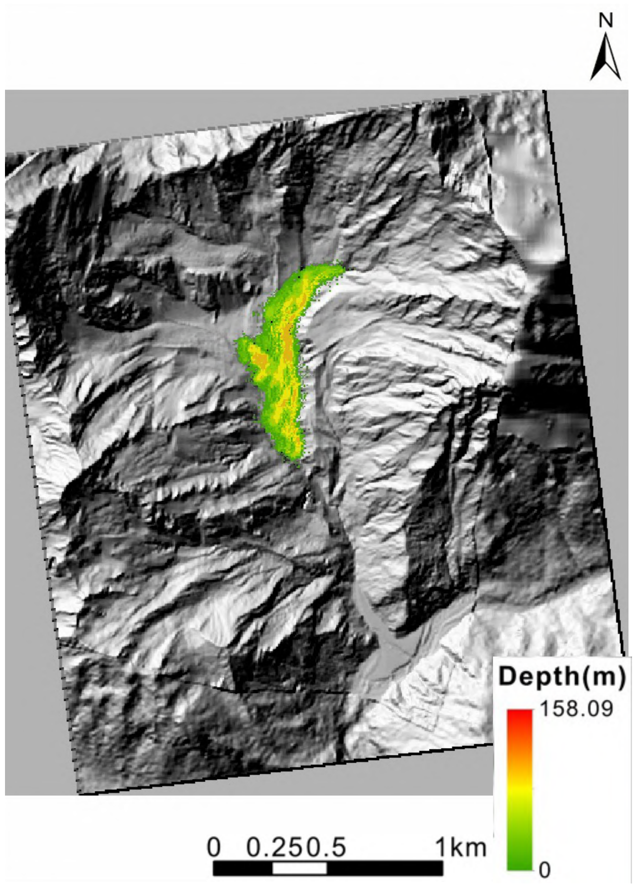
Scenario 1

70 Mm^3 source volume



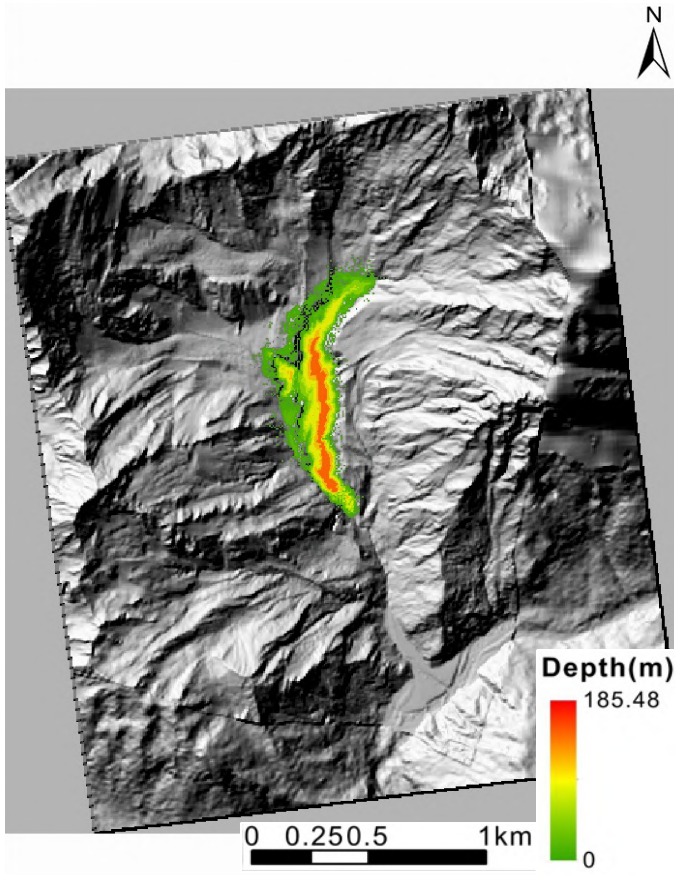
Scenario 2

210 Mm^3 source volume

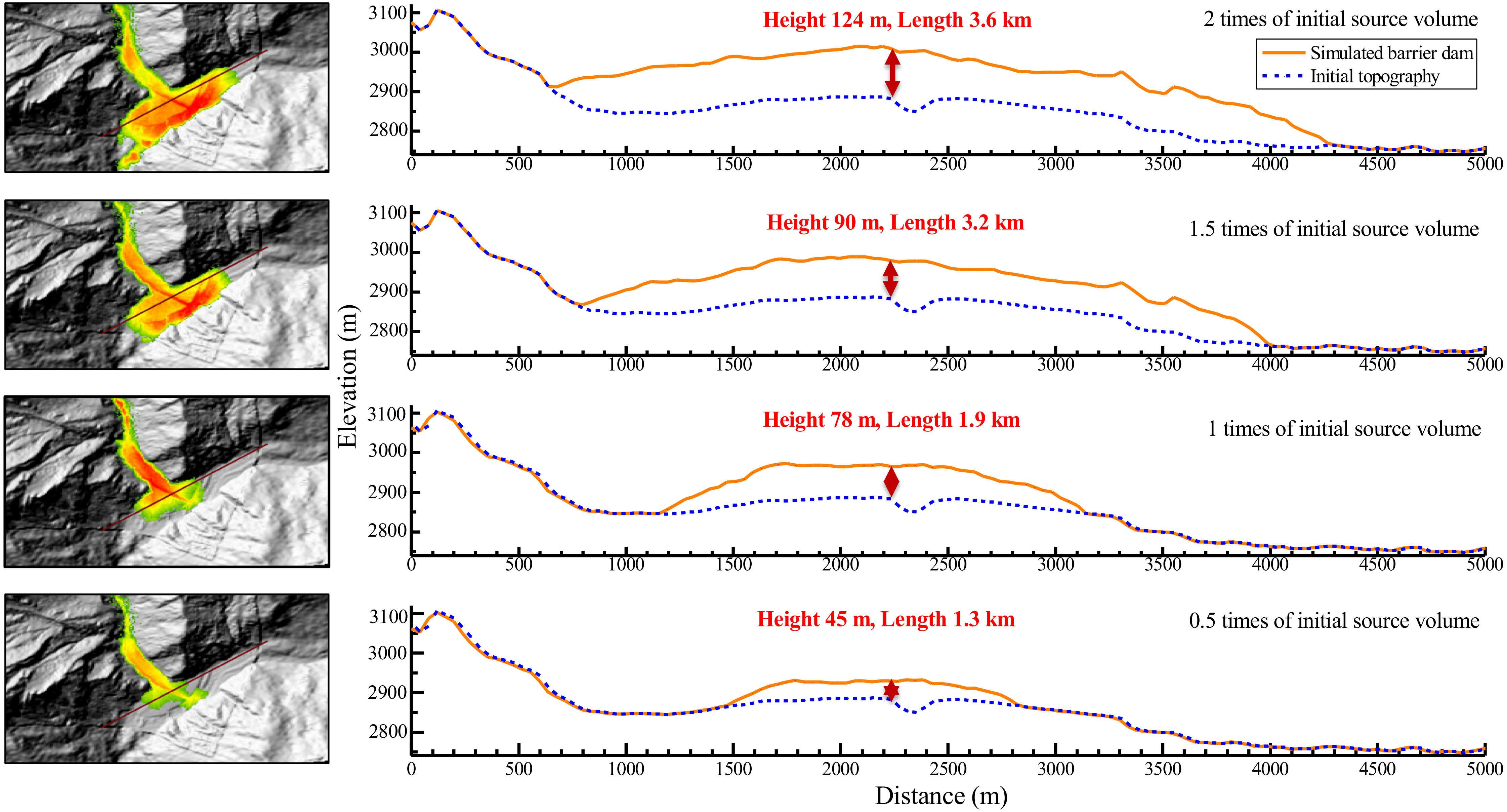


Scenario 3

280 Mm^3 source volume



Scenario-based prediction of future hazard



AGU ADVANCING EARTH AND SPACE SCIENCES

JGR Earth Surface

RESEARCH ARTICLE
10.1029/2023JF007115

How Ice Particles Increase Mobility of Rock-Ice Avalanches: Insights From Chute Flows Simulation of Granular Rock-Ice Mixtures by Discrete Element Method

Zetao Feng[1], Xuanmei Fan[1], Tao Ni[1], Yu Deng[1], Chengbin Zou[1], Jing Zhang[1], and Qiang Xu[1]

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Key Points:

- The rock-ice segregation and its effect on the mobility of rock-ice avalanches have been analyzed by using the discrete element method
- Rock-ice particle size ratio and volumetric ice content together determine the ice spatial distribution
- Ice spatial distribution and rock-ice particle size ratios jointly affect the mixture's mobility by controlling the collision stress

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Citation:
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Abstract

Rock-ice avalanches occurring in cold high-mountain regions often cause catastrophic damages due to their extremely high mobility. Rock and ice have different physical properties, such as particle size, density, friction, etc., leading to the segregation of rock and ice in the mixture and impacting its mobility. However, how ice affects the mobility of rock-ice avalanches is still poorly understood. A series of numerical experiments were conducted by using the discrete element method to quantify the effect of rock-ice particle size ratio and ice content on the particle segregation and mobility of their mixtures. Results show that rock-ice particle size ratio and volumetric ice content determine the spatial distribution of ice, thereafter affecting the mobility of the rock-ice mixture by controlling the ratio of particle collision stress and coulomb friction stress. In particular, different from conventional understanding, the ice spatial distribution can have a significantly greater influence on the mixture's mobility compared to the volumetric ice content in some scenarios. This study provides insights into the effect of granular ice on the mobility law in the early phase of rock-ice avalanches and has important implications for their hazard assessment.

Plain Language Summary

Rock-ice avalanche is a special type of earth surface process in alpine glacial regions, which has extremely high mobility, complex movement mechanisms, and enormous damage potential due to the existence of ice. Understanding how the ice affects the mixture's mobility is essential for assessing and preventing rock-ice avalanches and other related mass movements. In this study, the discrete element method was employed to conduct a series of numerical experiments aimed at investigating the influence of ice in rock-ice avalanches, where the mixtures of geomaterials were assumed to be composed of rock and ice particles associated with different particle sizes, densities and frictions. We found that the rock-ice particle size ratio and ice volumetric content control the segregation of rock and ice particles. The segregation determines the ice spatial distribution in the mixture, which together with the ice particle size affect the rock-ice mixture's mobility by controlling the ratio of particle collision stress and coulomb friction stress. Our finding has important implications in risk assessment and prevention of glacier-related mass movements.

1. Introduction

Alpine glacial regions are sensitive and generally respond quickly to climate change (Evans & Clague, 1988; Evans et al., 2021; Fan et al., 2022; Haeberli, 1997; Yang et al., 2019). With global warming trends, rock-ice avalanches and its process chains may significantly increase in frequency and magnitude (Allen et al., 2011; Fan et al., 2022; Fischer et al., 2013; Huggel, 2009; Mergili, Emmer, et al., 2018; Mergili, Frank, et al., 2018; Mergili et al., 2017, 2020). Since 2014, several rock-ice avalanches and the resulting process chains have occurred in Sedongpu gully of the Yarlung Zangbo basin, Tibet, China, indicating that the frequency of hazards is gradually increasing (W. Li et al., 2022). On 7 February 2021, a catastrophic rock-ice avalanches disaster chain descended the Ronti Gad and other valleys in Chamoli, India, destroying two hydropower projects and causing widespread devastation (Fan et al., 2022; Shugar et al., 2021). The number of casualties, including both fatalities and missing individuals, has exceeded 200 in this incident. Rock-ice avalanches tragically demonstrate extremely high mobility and catastrophic potential (Evans & Clague, 1988; Huggel et al., 2007; Schneider, Huggel, et al., 2011; Schneider, Kaitna, et al., 2011; Sosio, 2015; Sosio et al., 2012; Yang et al., 2019), which are among the most dangerous natural disasters (Pudasaini & Krautblatter, 2014; Pudasaini & Miller, 2013; Yang et al., 2019).

Unfortunately, the low frequency, abrupt initiation, remote location, and unpredictable nature of rock-ice avalanches pose significant challenges for conducting direct field observations and measurements (Yang et al., 2019). The

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ELSEVIER

Combining geophysics, remote sensing and numerical simulation to assess GLOFs: Case study of the Namulacuo Lake in the Southeastern Tibetan Plateau

Liyang Jiang, Xuanmei Fan *, Yu Deng, Chengbin Zou, Zetao Feng, Danny Love Wamba Djukem, Tao Wei, Xiangyang Dou, Qiang Xu

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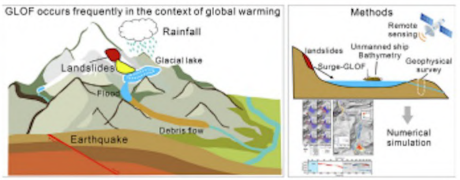
H I G H L I G H T S

- Rare field survey data of high-altitude glacial lakes are obtained.
- Integrated diagnosis approach is proposed.
- Geophysical techniques are applicable to the diagnosis of glacial lake.
- Freeze-thaw cycles can lead to glacial lake outburst.
- The dam of the glacial lake may have been formed by multiple landslides.

G R A P H I C A L A B S T R A C T



A R T I C L E I N F O

Editor: Fernando A.L. Pacheco

Keywords:
GLOF
Geophysical technique
SBAS-InSAR
Multi-phase mass flow modeling
Numerical simulation
r.avaflow

A B S T R A C T

The current highest glacial lake outburst floods (GLOFs) risk level is centered in the eastern Himalaya. GLOFs represent a serious threat to downstream inhabitants and ecological environment. In the context of climate warming on the Tibetan Plateau, such GLOFs will continue or even intensify in the future. Remote sensing and statistical methods are often used to diagnose glacial lakes with the highest outburst probability. These methods are efficient in large-scale glacial lake risk assessment but do not take into consideration the complexity of specific glacial lake dynamics and triggering factor uncertainty. Therefore, we explored a novel approach to integrate geophysics, remote sensing, and numerical simulation in glacial lake and GLOF disaster chain assessments. In particular, geophysical techniques are rarely applied to the exploration of glacial lakes. The Namulacuo Lake located in the southeastern Tibetan Plateau is considered as the experimental site. The current status of the lake, including landform construction and identifying potential triggering factors, was first investigated. Secondly, the outburst process and disaster chain effect were evaluated by numerical simulation based on the multi-phase modeling frame proposed by Pudasaini and Mergili (2019) implemented in the open source computational tool r.avaflow. The results allowed verifying that the Namulacuo Lake dam was a landslide dam with an obvious layered structure. Also, the piping-induced flood might have more severe consequences than the short-term ultra-high discharge flood caused by surge. The blocking event caused by a surge disappeared faster than that caused by piping. Therefore, this comprehensive diagnostic approach can assist GLOF researchers to increase their understanding of key challenges they are facing regarding GLOF mechanisms.

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DOI: 10.1002/ldr.4870

RESEARCH ARTICLE

WILEY

The response of glaciers and glacial lakes to climate change in the Southeastern Tibetan Plateau over the past three decades

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Abstract

With global warming, changes in glaciers and glacial lakes on the Tibetan Plateau call for a serious inspection. The Southeastern Tibetan Plateau (SETP) is a typical monsoonal marine glacier area that is extremely vulnerable to climate change. It is affected by both humid and warm Indian Ocean currents. Outlines of glaciers and glacial lakes in SETP have been extracted from Landsat satellite images with an automatic extraction method based on image compositing with Google Earth Engine and Random Forest algorithm. Alongside the outlines, meteorological data have been collected from 1990 to 2021. The results show that since 1990 the glacier area of SETP has retreated by about 2165.33 km^2 (~25.28%), the glacial lake area has increased by about 36.41 km^2 (~21.45%), and their number has increased by 477 (~27.32%). The reliability and scientific validity of this study is proven by comparison with existing glacier inventories. By analyzing the meteorological data, the inverse correlation between the glacier area and temperature has been found. Despite decreases in cumulative precipitation, the glacial lake level rise and consequent area expansion have been observed. A fitting equation for the response pattern of glacier changes to temperature and precipitation change is presented and will provide a basis for future studies.

KEYWORDS
climate change, glacial lake inventory, glacier inventory, quantitative relationship, Southeastern Tibetan Plateau

1 | INTRODUCTION

Tibetan Plateau (TP) incorporates the most glaciers outside Arctic and Antarctic both in terms of number and total area (X. Yao et al., 2017), for this reason, it is sometimes referred to "Third Pole" (Qiu, 2008; T. D. Yao, Thompson, et al., 2022). In conjunction, TP contains many great glacial lakes, thus acting as a sort of "Asian Water Tower" (T. D. Yao, Bolch, et al., 2022), where numerous Asian rivers originate (Barnett et al., 2005; Immerzeel et al., 2010). These rivers flow through many lands and nations, both in China and Southeast Asia, and are crucial to a diverse range of human and natural ecosystems (Dou et al., 2023; Immerzeel et al., 2010; Immerzeel & Bierkens, 2010).

Many studies about glaciers, glacial lakes, and their relation to climate change in TP have been published in recent years, which thoroughly illustrate the close connection of glaciers, glacial lake changes, and climate change in the TP (T. D. Yao et al., 2012; G. Q. Zhang, Yao, et al., 2020). Many global glacier mapping inventories have been published thanks to the Global Land Ice Space Survey (GLIMS) project, among these, some addressed the inventory gap in TP (Paul et al., 2013; Raup et al., 2007, 2013). Most relevant for the TP are as follows: the Randolph Glacier Inventory (RGI), which has been continuously updated till version 6.0 at the time of writing this study (Arendt et al., 2017; Pfeffer et al., 2014), and Glacier Area Mapping for Discharge from the Asian Mountains (GAMDAM), which is done

Conclusions and outlooks

- **Undertaking a hazard and risk assessment of the chain of geo-hazards (multiple cascading hazards) caused by large magnitude earthquakes. *The challenge is particularly great given the difficulties in quantifying the interaction between hazards.***
- **The mechanism of the initiation and runout dynamics of geohazards in glacier-covered cold regions is almost unknown, needs more attentions.**
- **Developing physics-based numerical models for future hazard prediction is crucial for risk reduction;**
- **The coupling effect of tectonic and climatic forces on geological hazards is not well studied, and it requires multi-disciplinary research in the future.**

Thanks to my team and all the collaborators!