Regional Simulations of Three-Dimensional Rainfall-Induced Landslides: The example of Hurricane Maria in Puerto Rico

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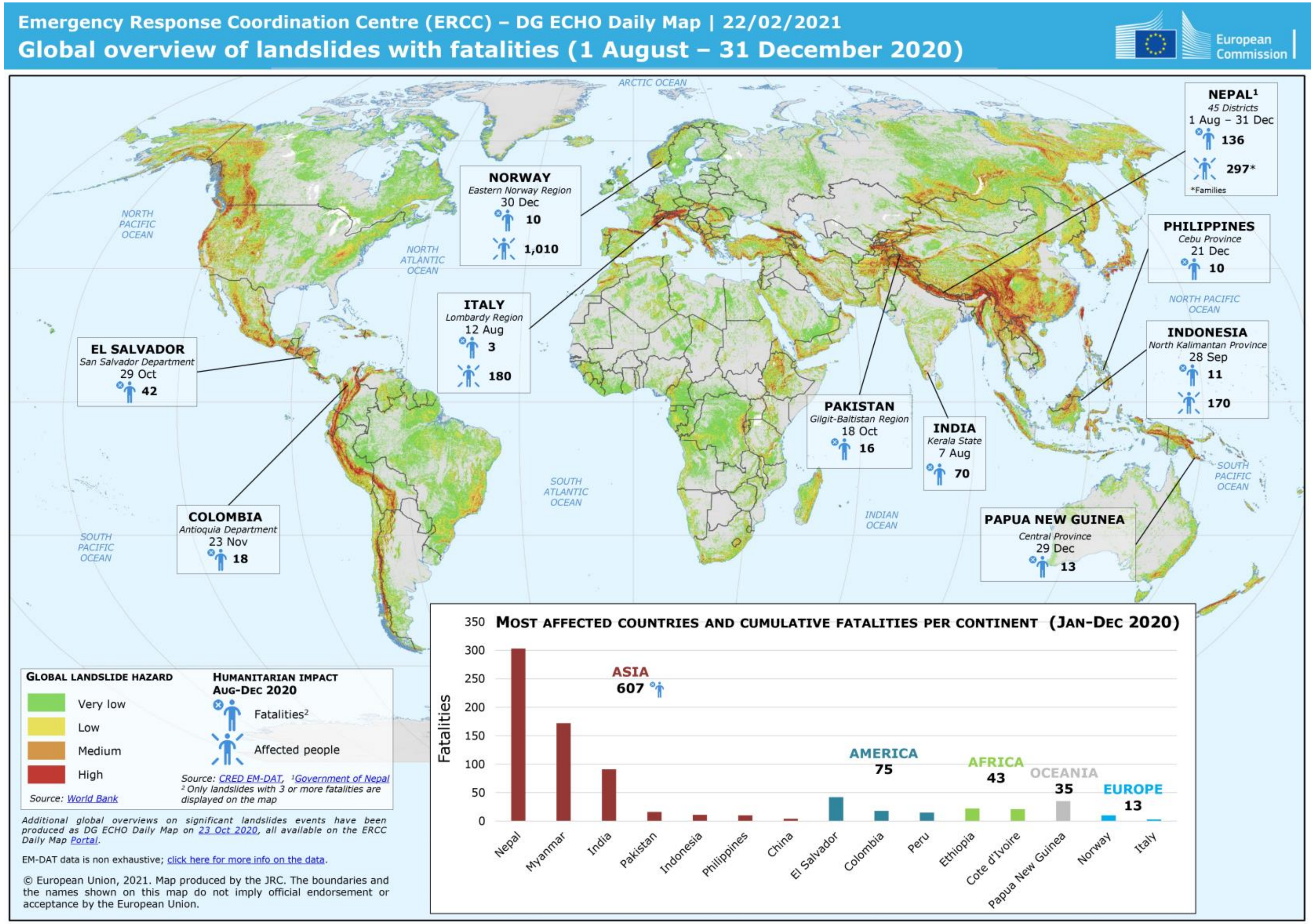
03/26/2025

Berkeley Engineering

Why is Landslide Prediction Necessary?



Emergency Response Coordination Centre (ERCC) – DG ECHO Daily Map | 22/02/2021

Global overview of landslides with fatalities (1 August – 31 December 2020)

Additional global overviews on significant landslides events have been produced as DG ECHO Daily Map on 23 Oct 2020, all available on the ERCC Daily Map Portal.

EM-DAT data is non exhaustive; click here for more info on the data.

© European Union, 2021. Map produced by the JRC. The boundaries and the names shown on this map do not imply official endorsement or acceptance by the European Union.

Source: CRED EM-DAT, [1]Government of Nepal

[2] Only landslides with 3 or more fatalities are displayed on the map

Source: World Bank

(European Commission's Directorate-General for European Civil Protection and Humanitarian Aid Operations, 2022)

Why is Landslide Prediction Necessary?

Philippines, February 2024

Why is Landslide Prediction Necessary?

Puerto Rico, Hurricane Maria, September 2017

Why is Landslide Prediction Necessary?

Berkeley Hills, January 2023

Why is Landslide Prediction Necessary?

Puerto Rico, Hurricane Fiona, November 2022

Why is Landslide Prediction Necessary?

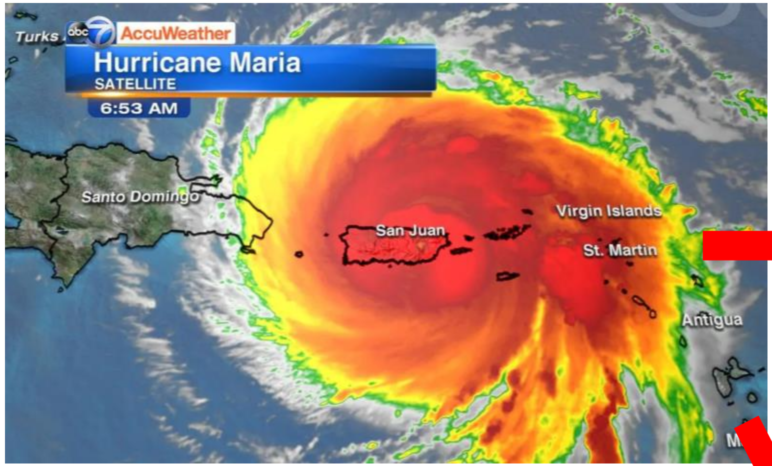
Towards a Community-Scale Landslides Resilience!

Kyodo News via AP

Hokkaido, Japan, September 2018

Cascading Hazards

Hurricane



Hurricane Maria, Puerto Rico (2017)

Flood

Louisiana floods, Hurricane Sandy (2016)

Debris Flow

Zurich, Switzerland Debris Flows (2017)

Earthquake

Shale map in Levkada (2015)

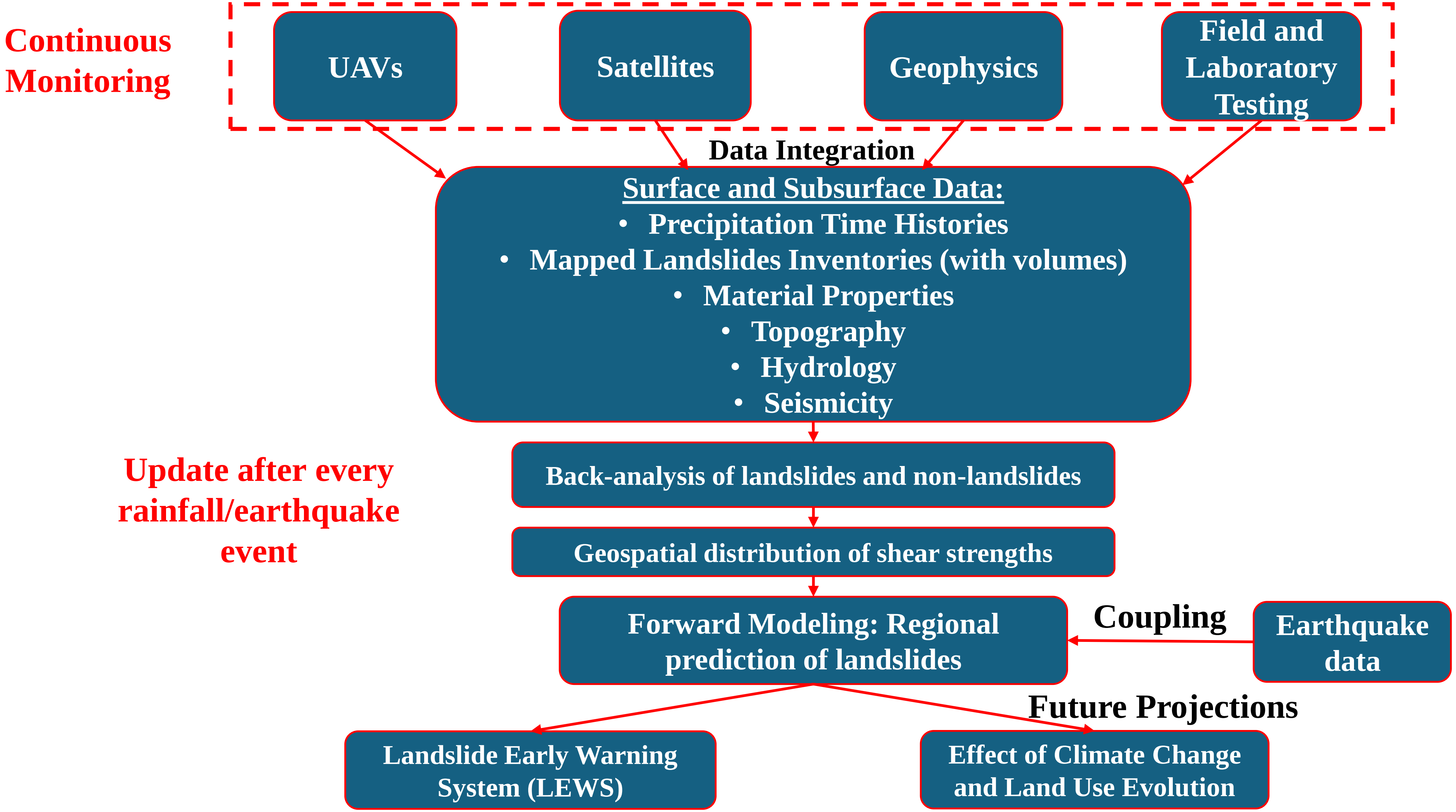
Landslide

Southern California Landslides (2024)

Landslide Runout

West Salt Creek Landslide (2014)

Research Vision



Continuous Monitoring

- UAVs
- Satellites
- Geophysics
- Field and Laboratory Testing

Data Integration

Surface and Subsurface Data:

- Precipitation Time Histories
- Mapped Landslides Inventories (with volumes)
- Material Properties
- Topography
- Hydrology
- Seismicity

Update after every rainfall/earthquake event

Back-analysis of landslides and non-landslides

Geospatial distribution of shear strengths

Forward Modeling: Regional prediction of landslides

Coupling

Earthquake data

Future Projections

Landslide Early Warning System (LEWS)

Effect of Climate Change and Land Use Evolution

Our Model: CRISIS (Coupled Regional Rainfall-Induced and Seismic Slope Instability Simulations)

ParFlow Hydrological Model

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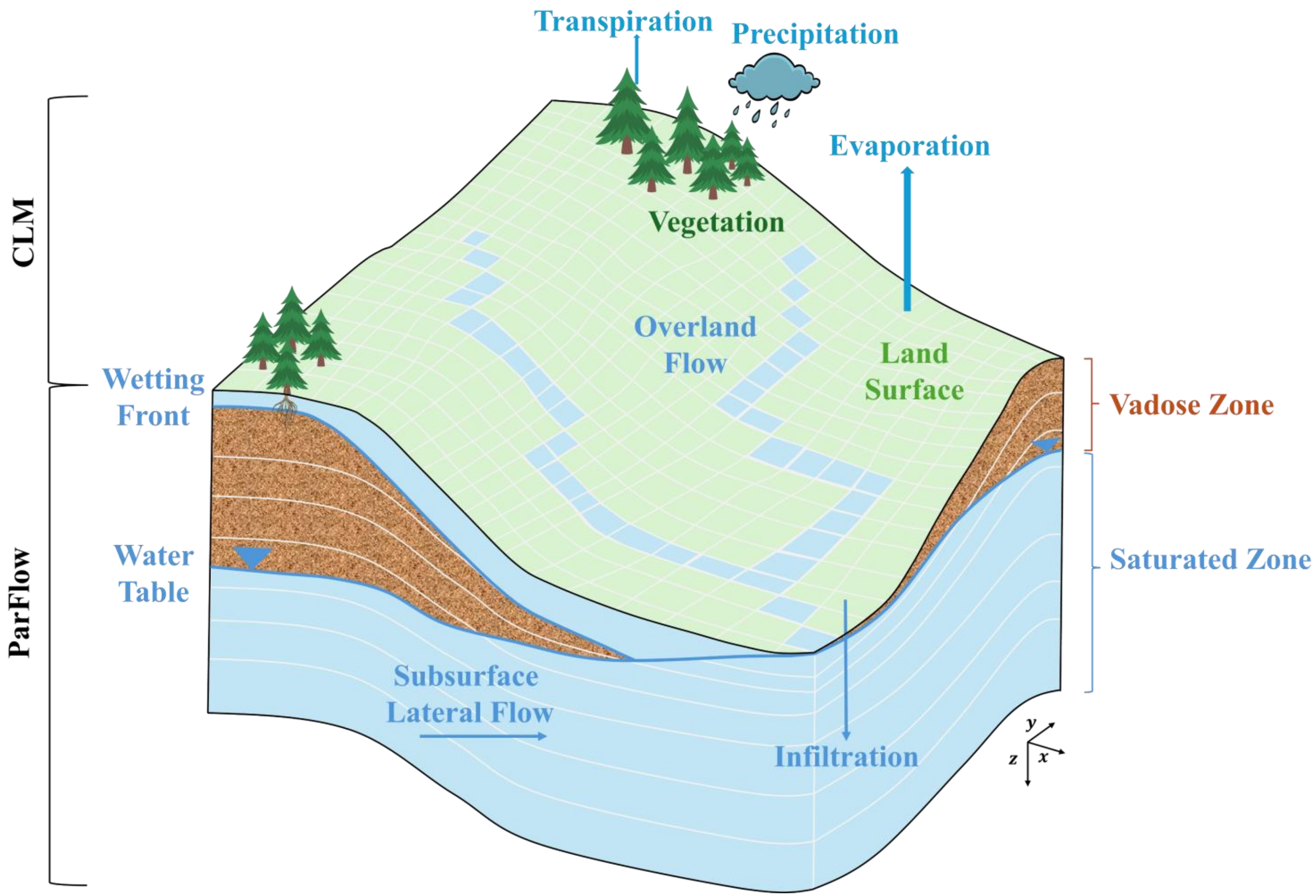
Pseudo-3D Slope Stability Approach

Hydrological Model: ParFlow

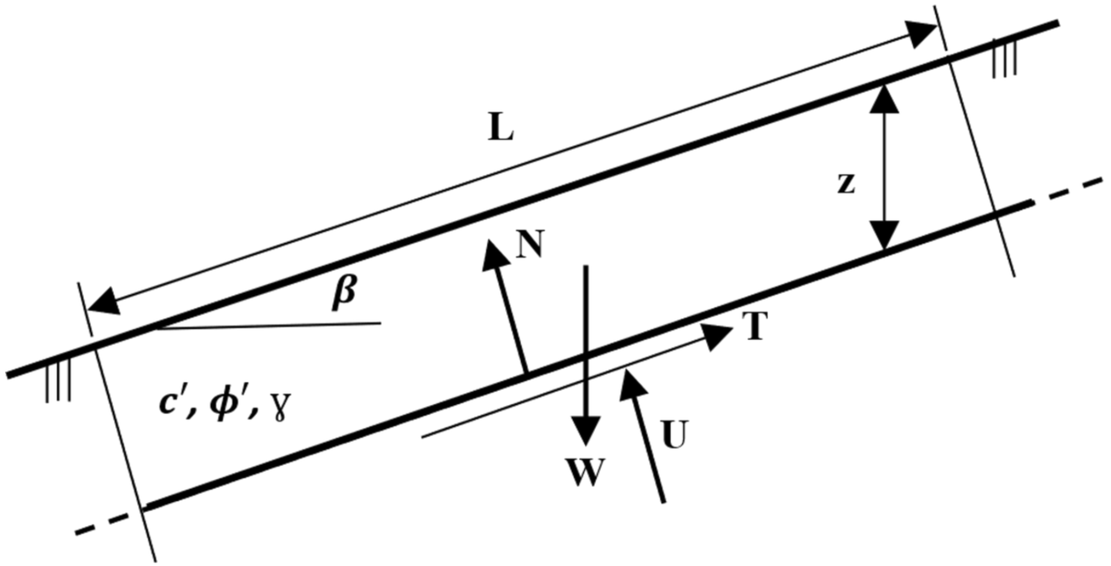


(Kollet and Maxwell, 2008)

- 3D subsurface groundwater flow: 3D Richard’s Equation
- Flow in both the saturated and vadose zones
- Transient Flow
- Precipitation time history
- Overland Flow
- Land surface processes: precipitation and evapotranspiration
- Hydrogeological modeling of the initial water table level: “Spinup” simulation
- Pore pressure heads that vary spatially, temporally, and in-depth

Pseudo-3D Slope Stability Approach

(a) 1D Infinite Slope Stability Analysis

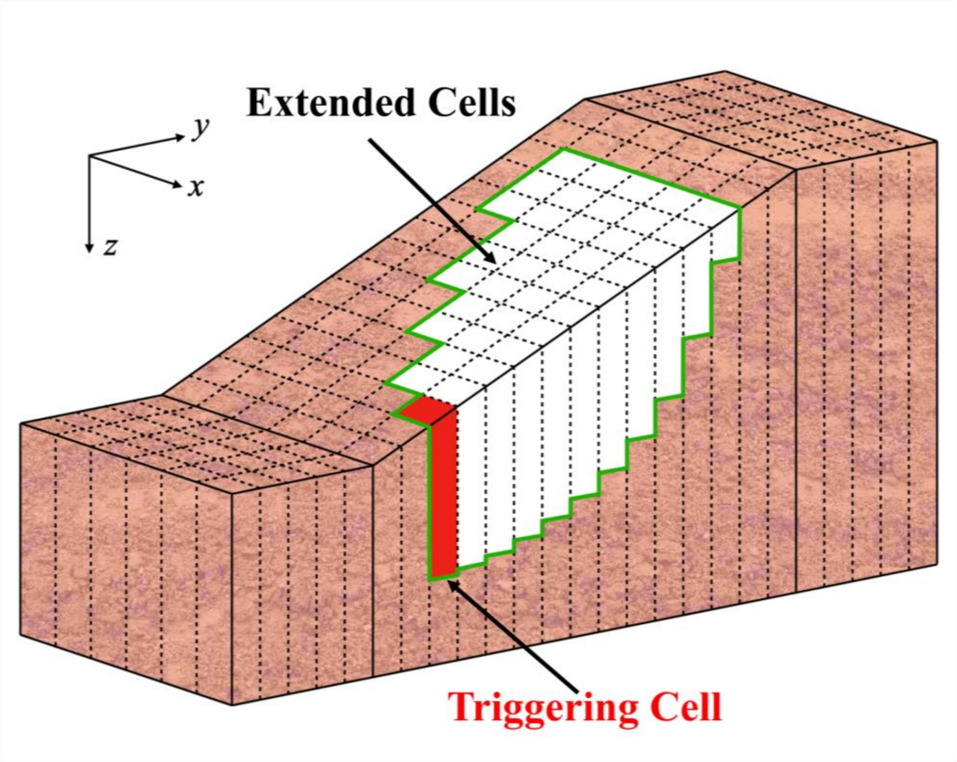


$$F_s(z,t) = \frac{\tan(\phi')}{\tan(\beta)} + \frac{c' - \psi(z,t)\,\gamma_w \tan(\phi')}{\gamma\, z\, sin(\beta)\, \cos(\beta)}$$

$\psi(z,t)$ is the pressure head at a certain time and depth, that accounts for suction

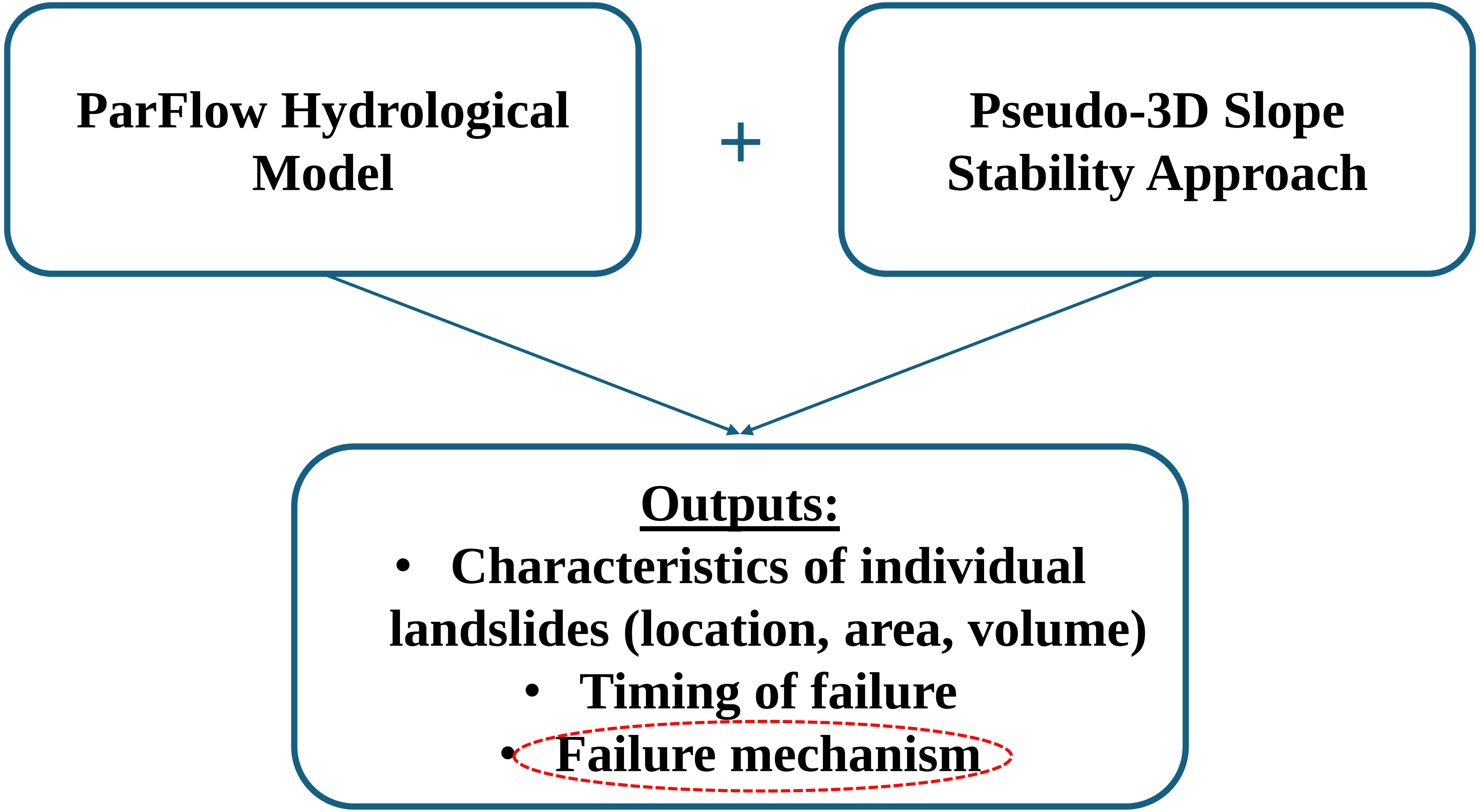
(Duncan et al., 2014)

(b) Geometric Projection to form 3D Landslides



(Gong et al. 2023)

Our Model: CRISIS (Coupled Regional Rainfall-Induced and Seismic Slope Instability Simulations)



ParFlow Hydrological Model

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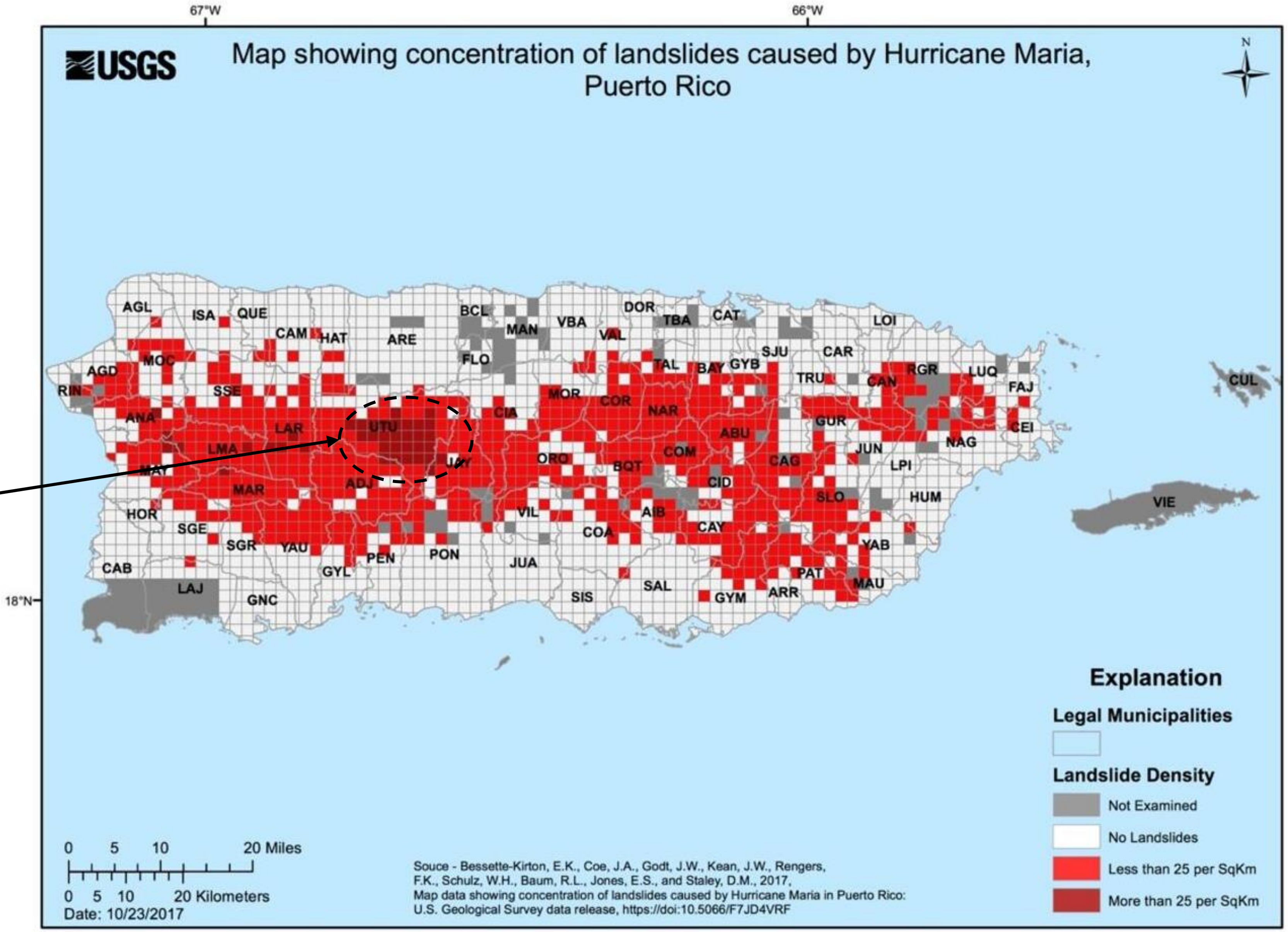
Pseudo-3D Slope Stability Approach

Outputs:

- **Characteristics of individual landslides (location, area, volume)**
- **Timing of failure**
- **Failure mechanism**

Hurricane Maria, Puerto Rico, September 2017



Map showing concentration of landslides caused by Hurricane Maria, Puerto Rico

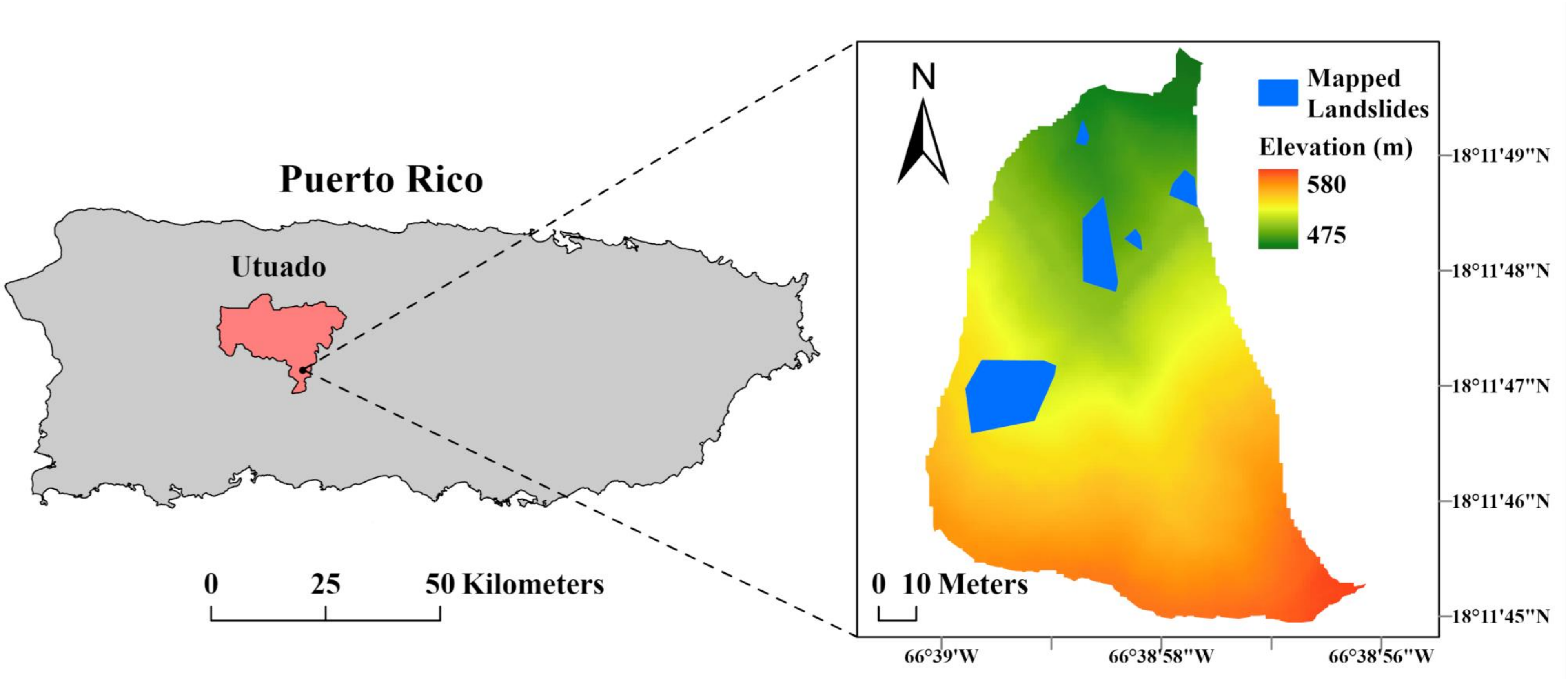
Date: 10/23/2017

Souce - Bessette-Kirton, E.K., Coe, J.A., Godt, J.W., Kean, J.W., Rengers, F.K., Schulz, W.H., Baum, R.L., Jones, E.S., and Staley, D.M., 2017, Map data showing concentration of landslides caused by Hurricane Maria in Puerto Rico: U.S. Geological Survey data release, https://doi:10.5066/F7JD4VRF

Utuado

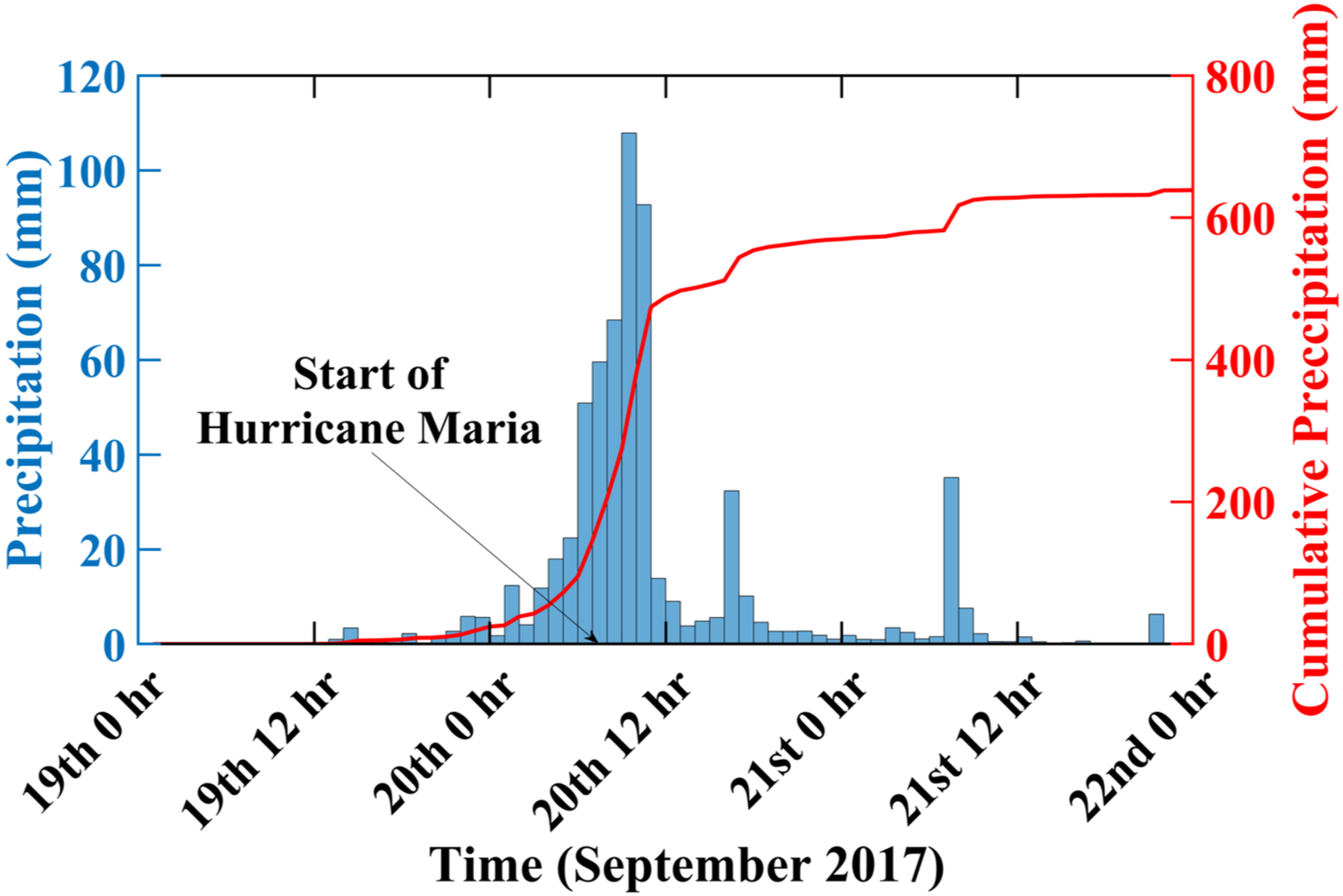
70,000 landslides and debris flows

Study Area: A Watershed in Utuado, Puerto Rico



Mapped landslide area density: 5.5%

Hurricane Maria Event



NCEP Stage IV Precipitation Dataset (Du 2011)

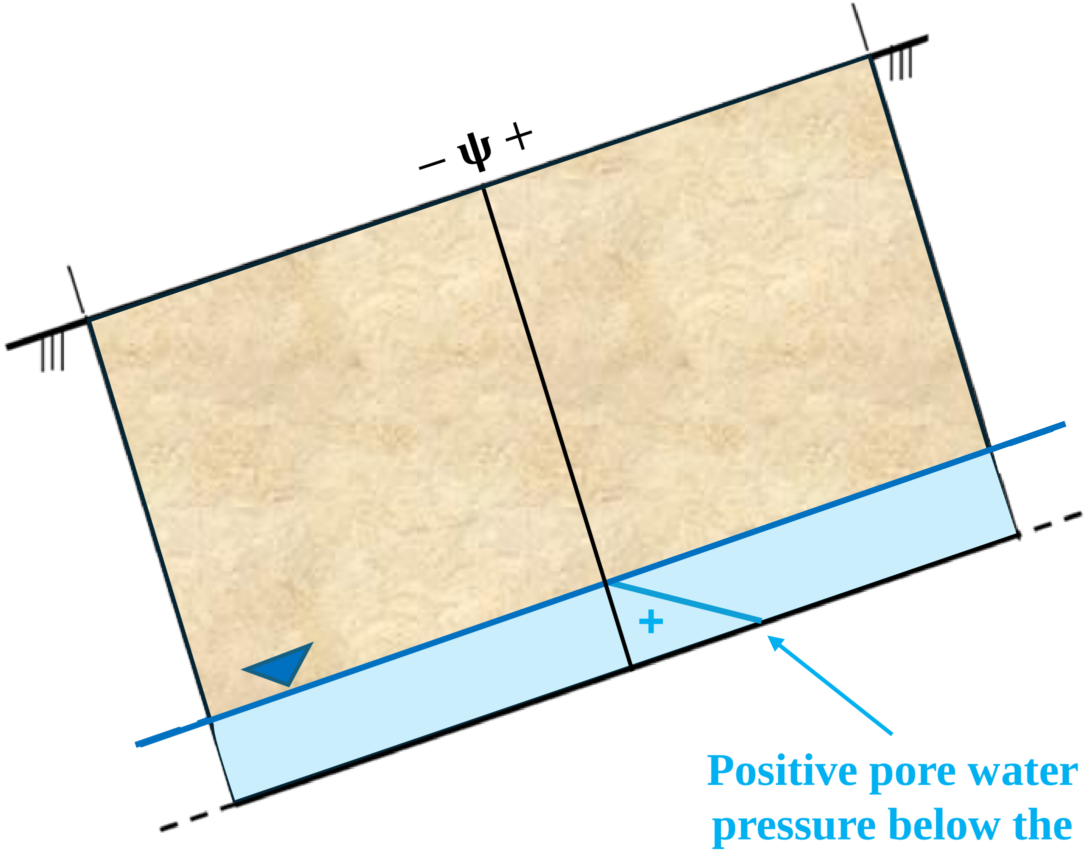
Model Input Parameters

Input Parameter	Value
Saturated hydraulic conductivity (k_s)	Variable
Hydraulic conductivity tensor	Isotropic
Specific storage	1e-05 m^{-1}
Porosity (n)	0.4
Van Genuchten α	1.0
Van Genuchten N	1.5
Saturated volumetric water content (θ_s)	0.45
Residual volumetric water content (θ_r)	0.1
Manning's coefficient	5.6e-05 $hr/m^{1/3}$
Constant recharge for the "spinup" ParFlow simulation	1e-08 m/s
IGBP vegetation class	2 (Evergreen broadleaf forests)
Rainfall dataset	NCEP Stage IV hourly rainfall rates
Cohesion (c')	Variable
Friction angle (ϕ')	Variable
Saturated soil unit weight (γ)	22 kN/m^3

Many parameters; Not all equally important; Sensitivity analysis conducted subsequently.

(1) Classical Bottom-up Failure

Initial Conditions:

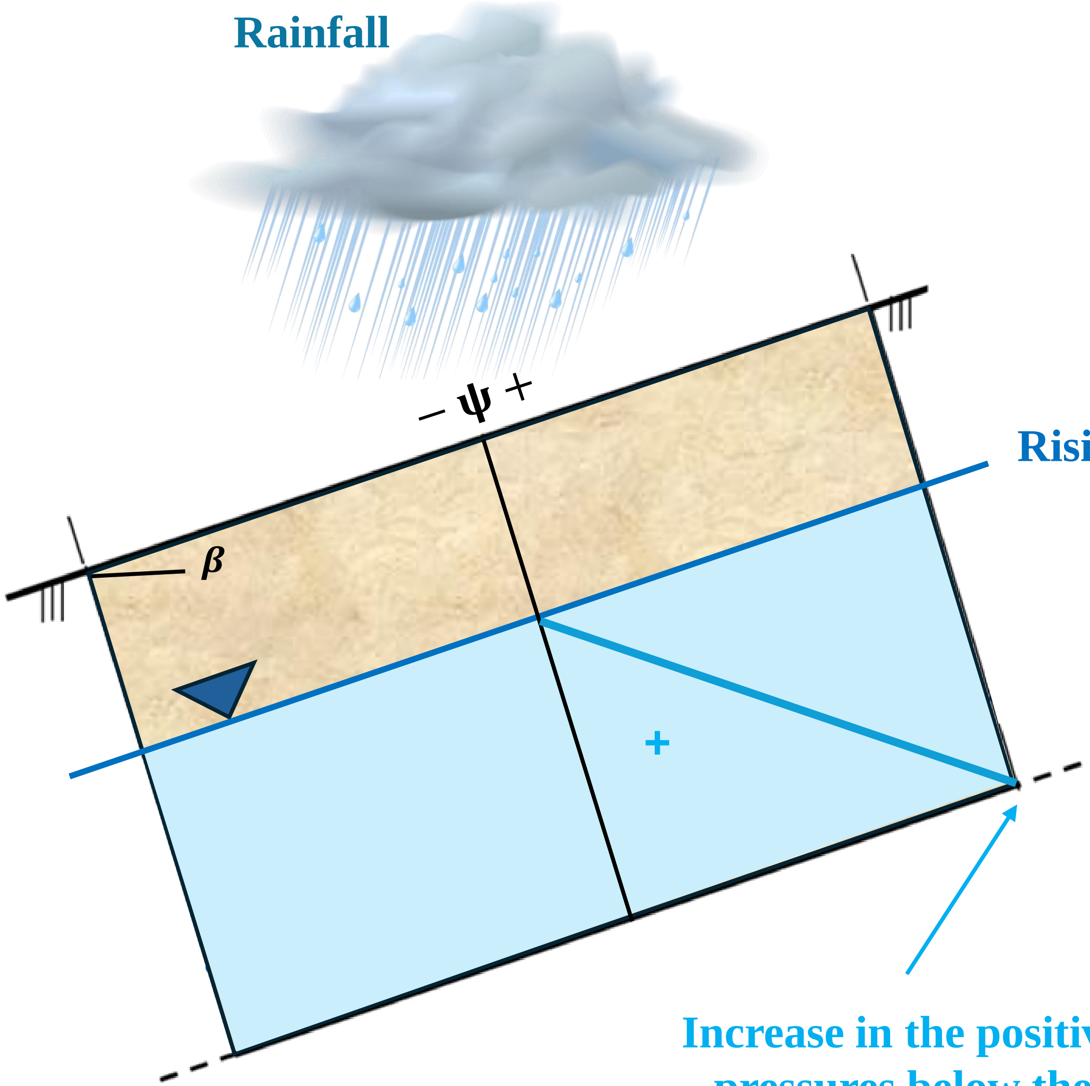


Initial ground water table

Positive pore water pressure below the water table

(1) Classical Bottom-up Failure

Amid Storm:

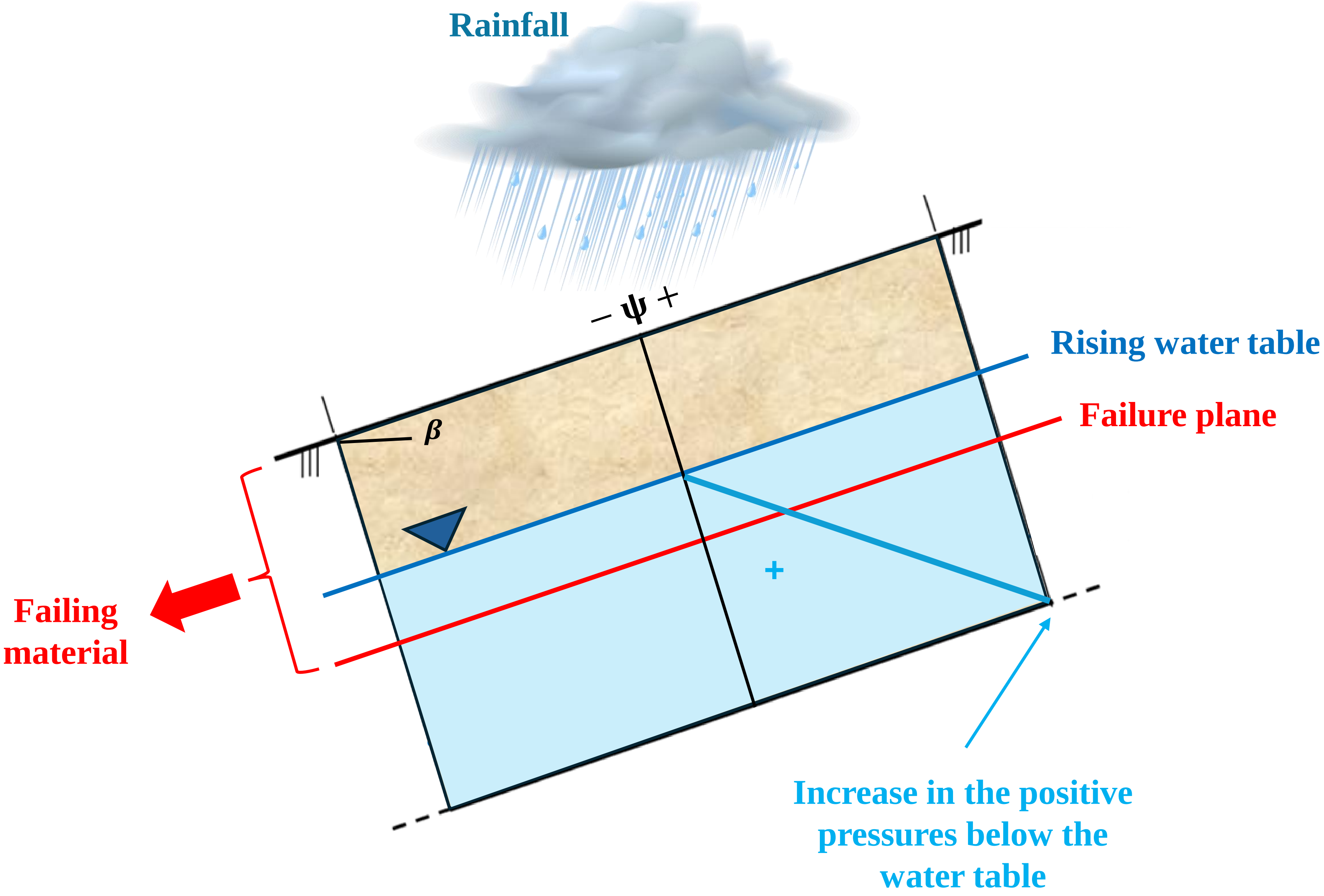


Rising water table

Increase in the positive pressures below the water table

(1) Classical Bottom-up Failure

Failure:

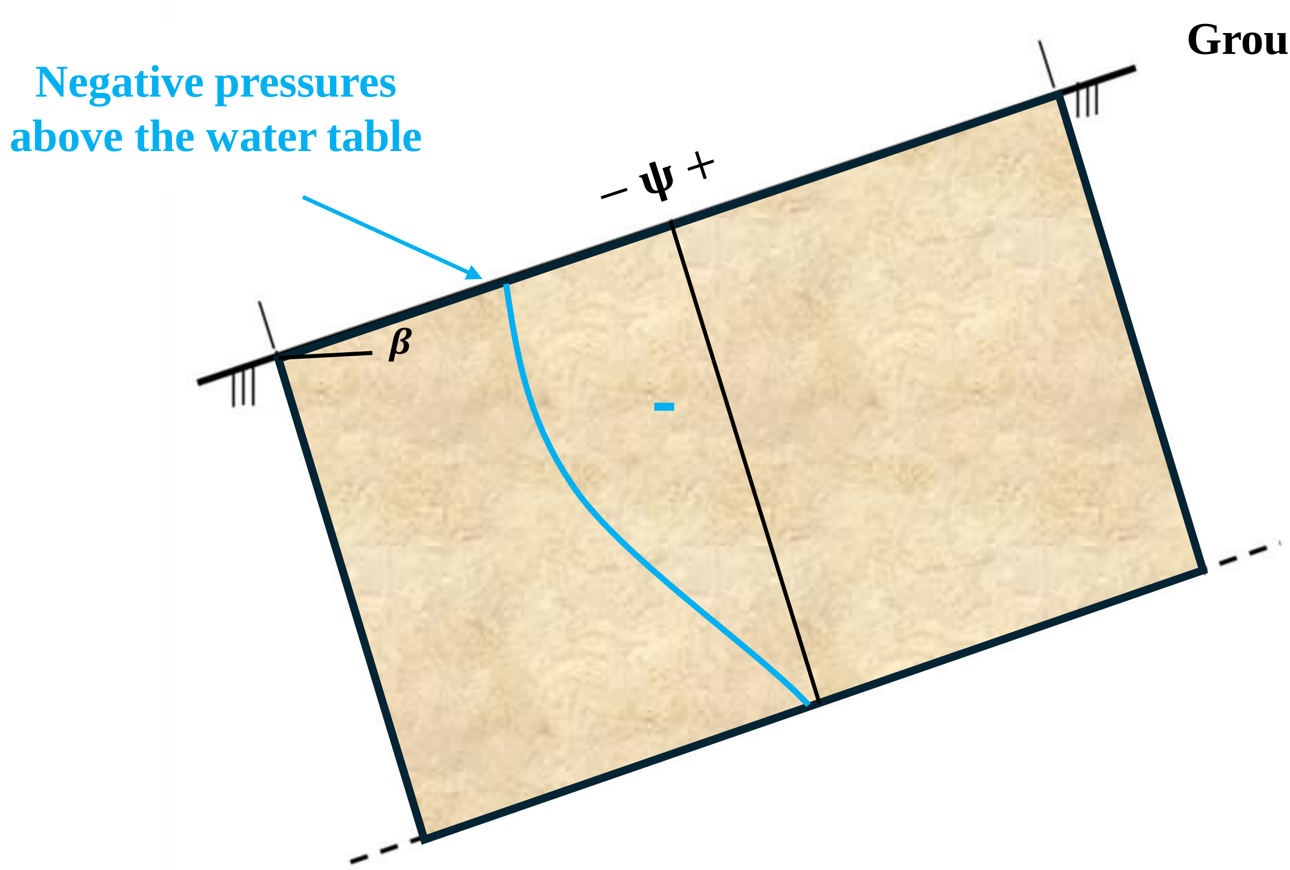


Did the water table rise all the way to the ridge top to trigger this landslide?

Hurricane Maria (2017)
Corozal, southwest of San Juan, Puerto Rico

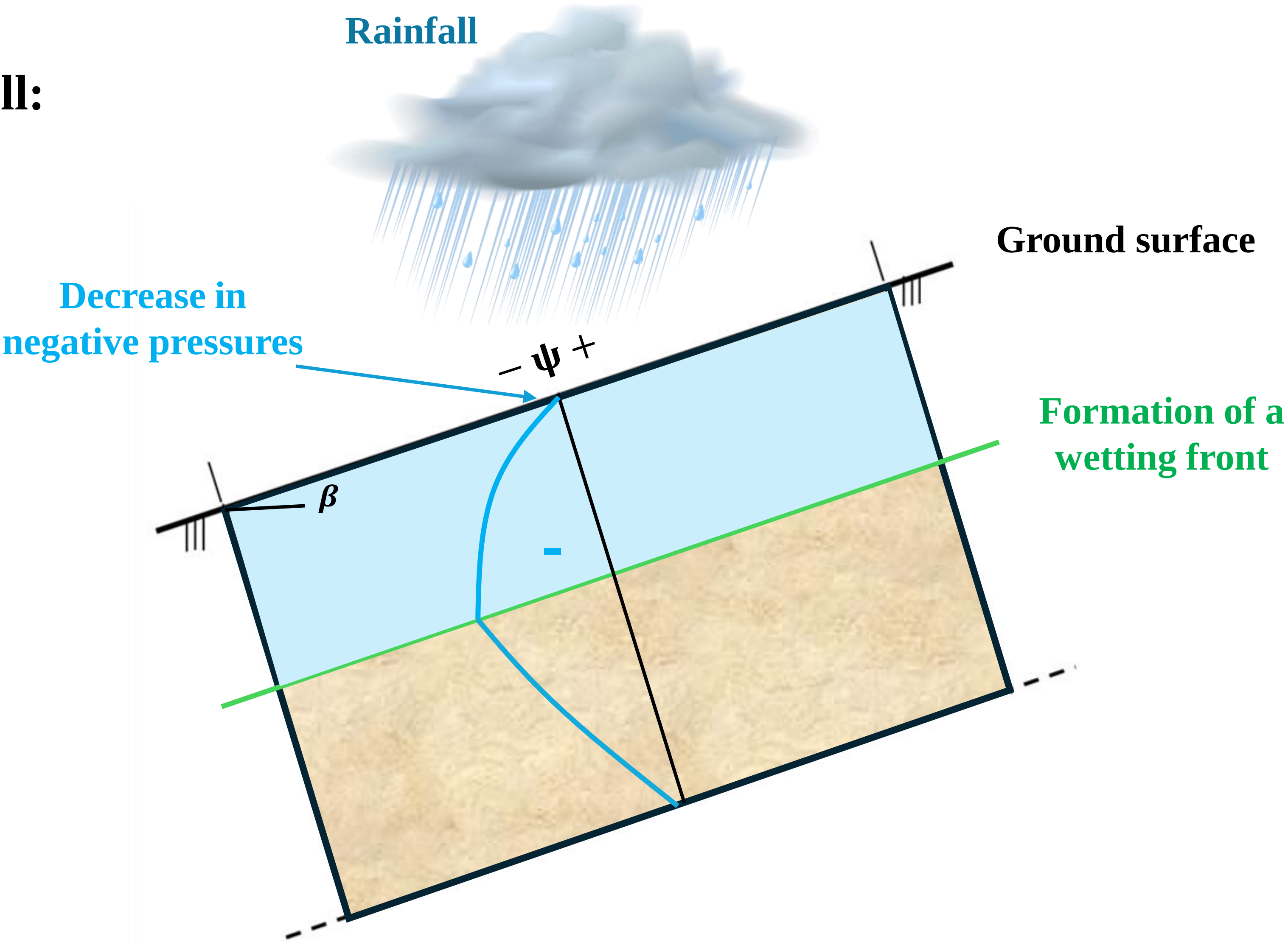
(2) Top-down Failure Mechanism: Wetting Front

Initial Conditions:



(2) Top-down Failure Mechanism: Wetting Front

Amid Rainfall:



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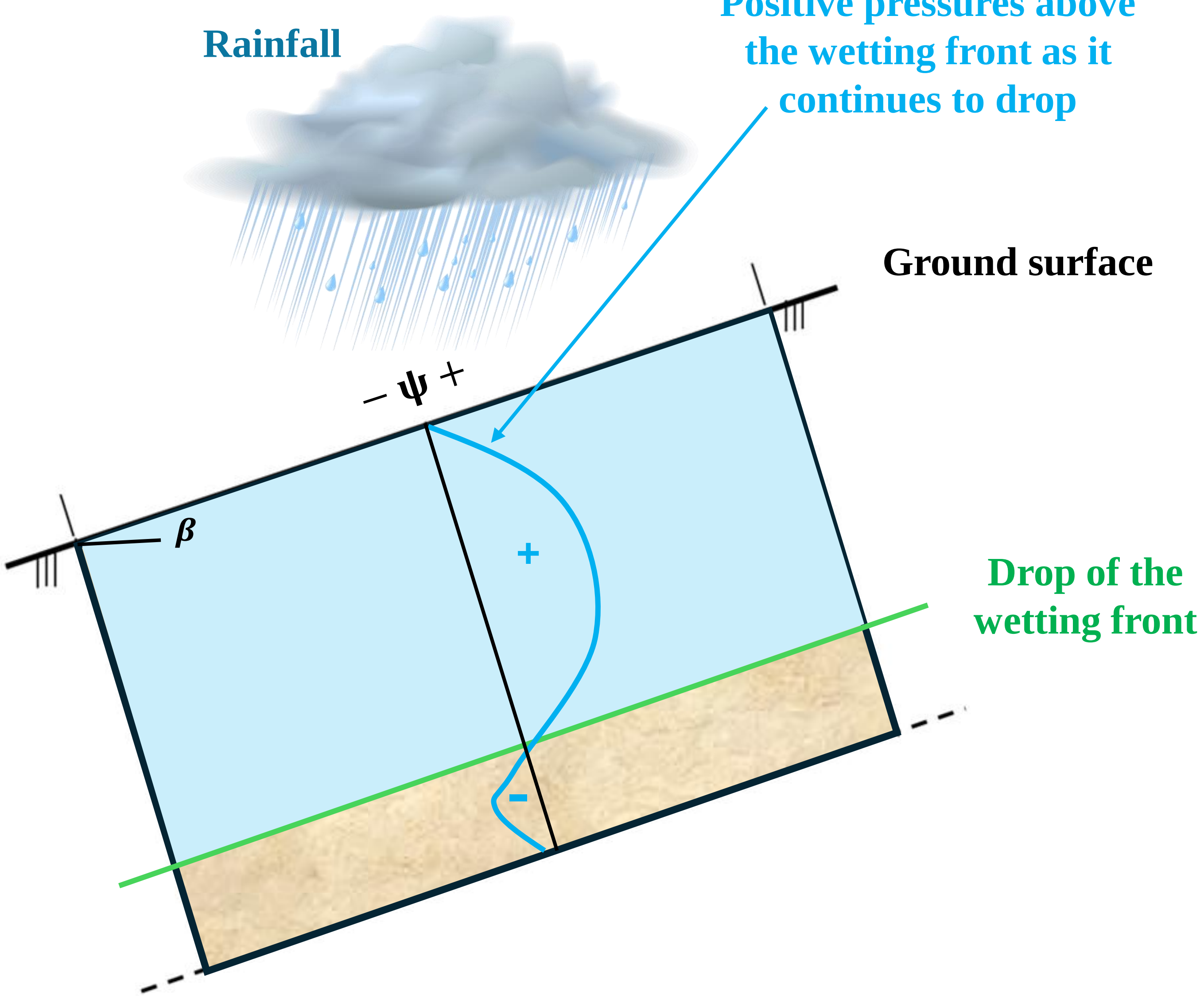
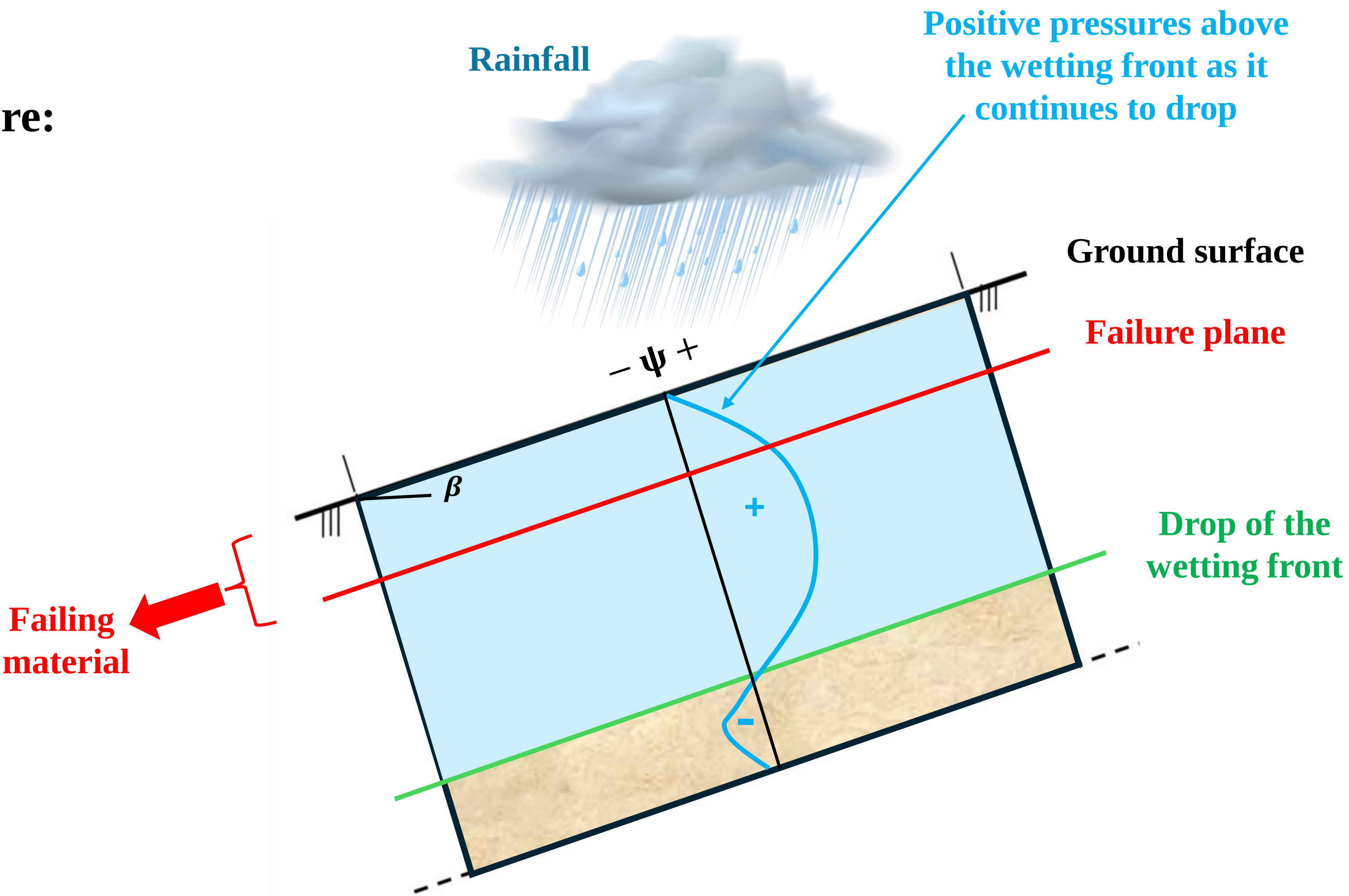


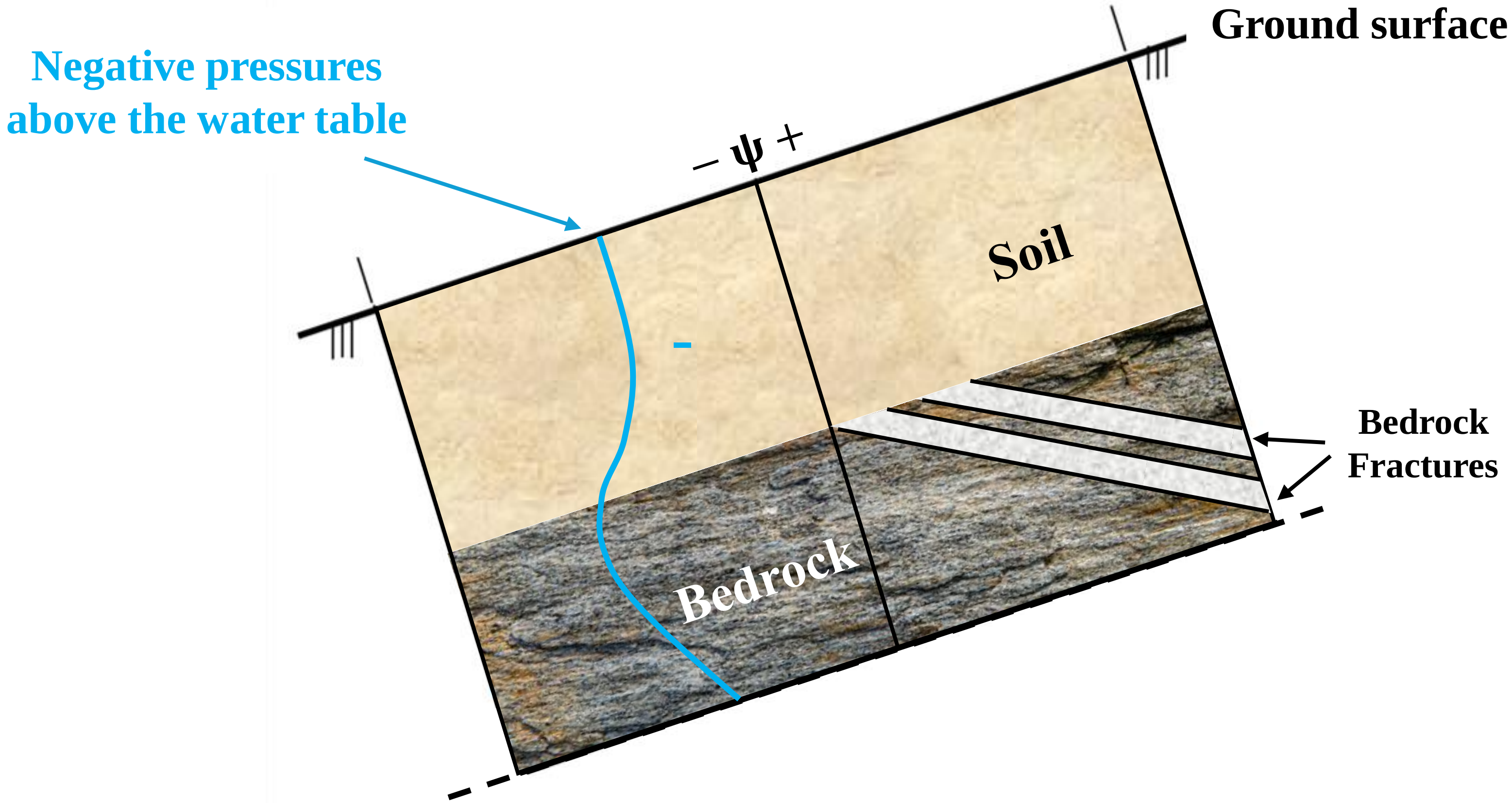
(2) Top-down Failure Mechanism: Wetting Front

Failure:



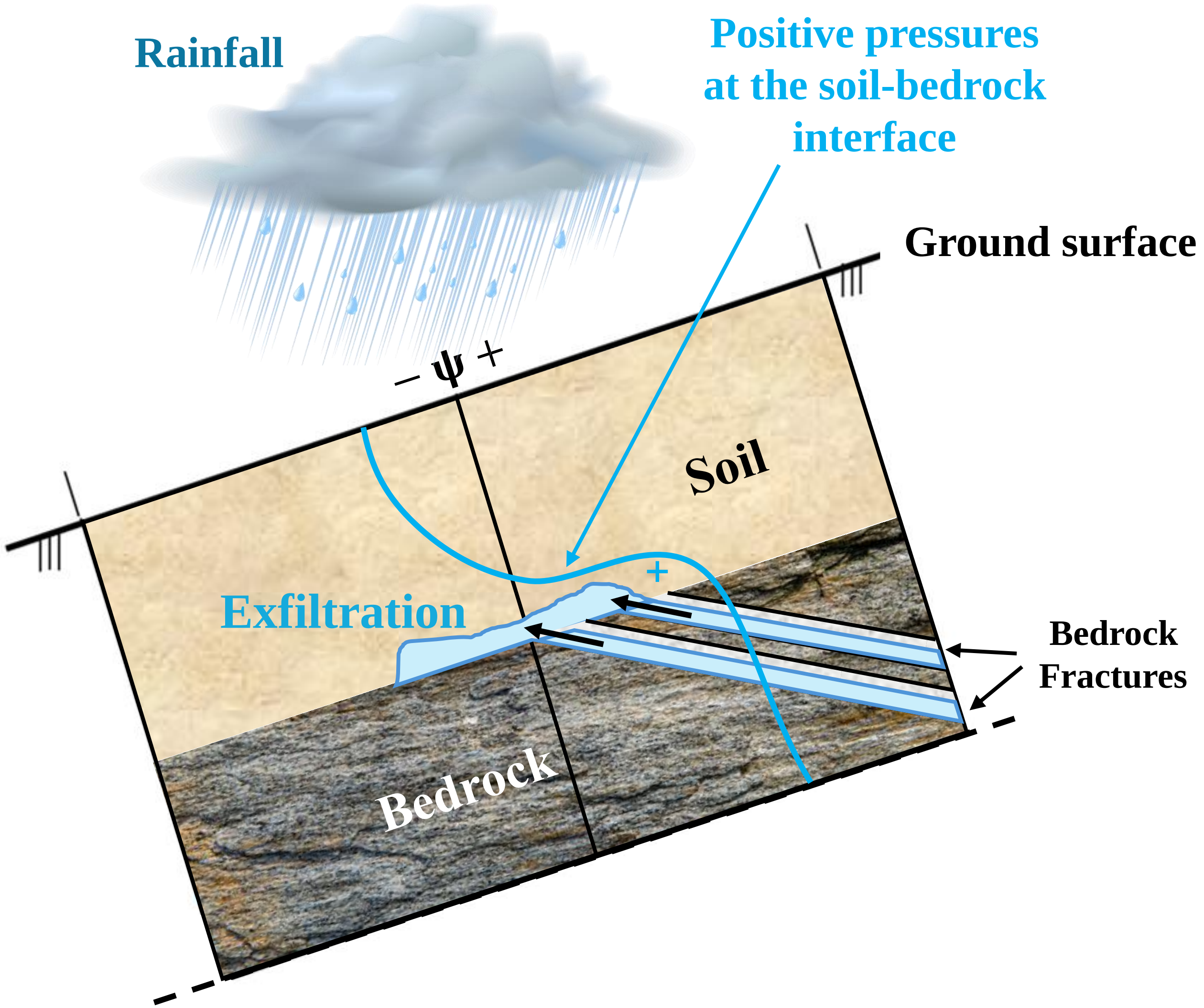
(3) Water Exfiltration from Highly Fractured Bedrock

Initial Conditions:



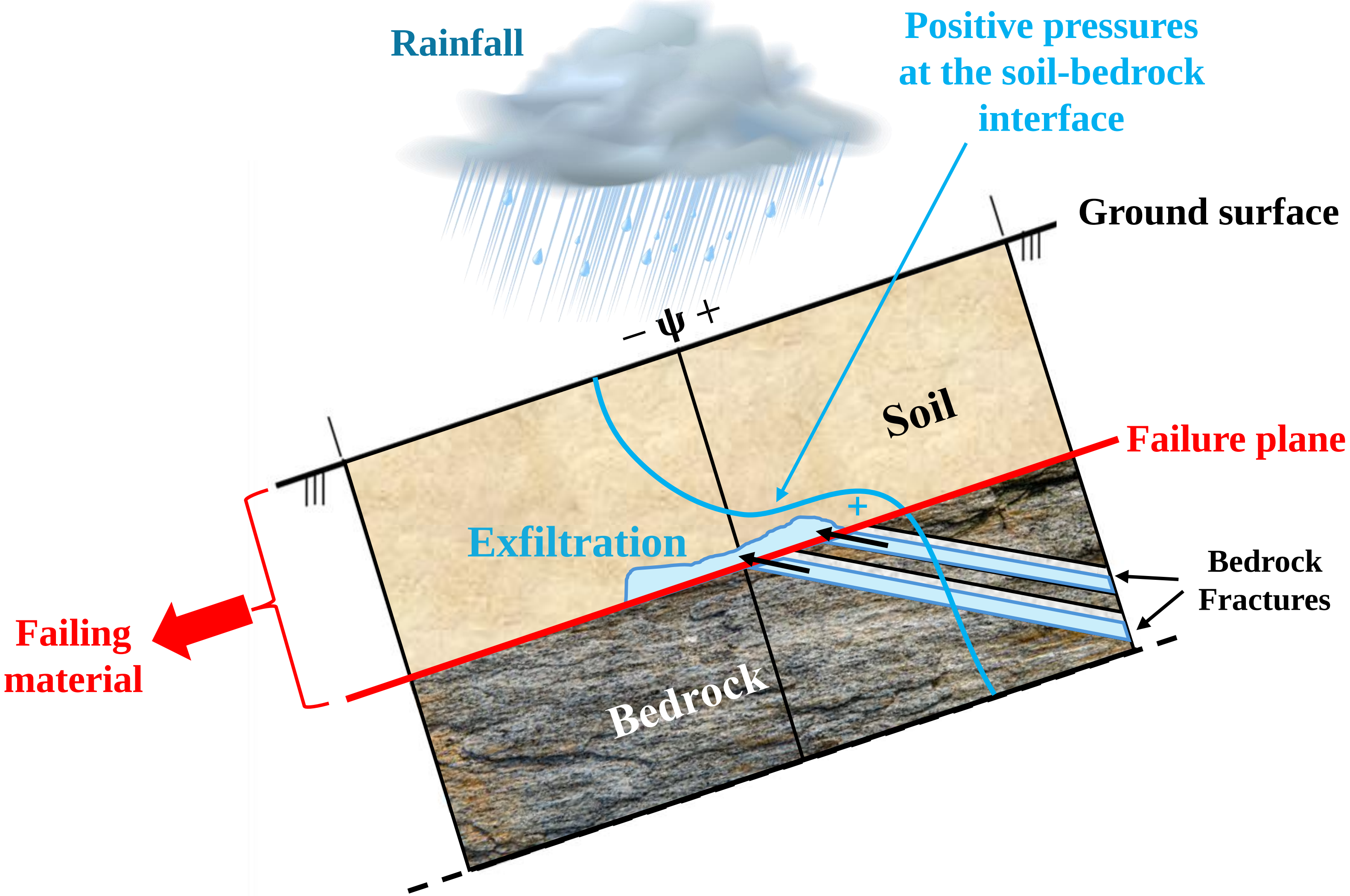
(3) Water Exfiltration from Highly Fractured Bedrock

Amid Rainfall:



(3) Water Exfiltration from Highly Fractured Bedrock

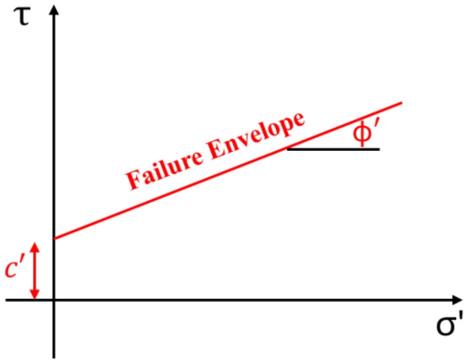
Failure:



Which Failure Mechanism Dominates?

Geomorphic Position

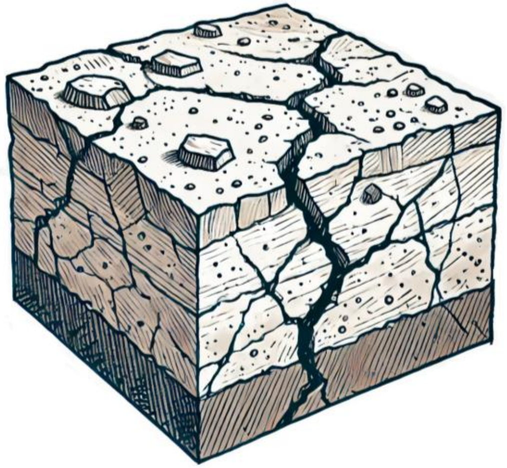
Ground Shear Strength



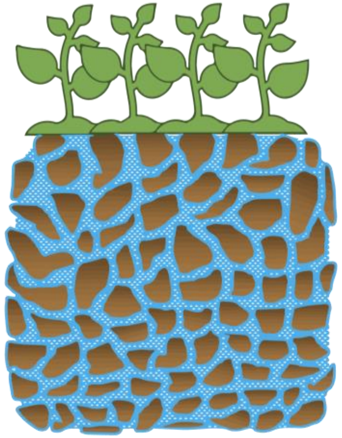
Storm Characteristics

Subsurface Soil Type

Bedrock Characteristics

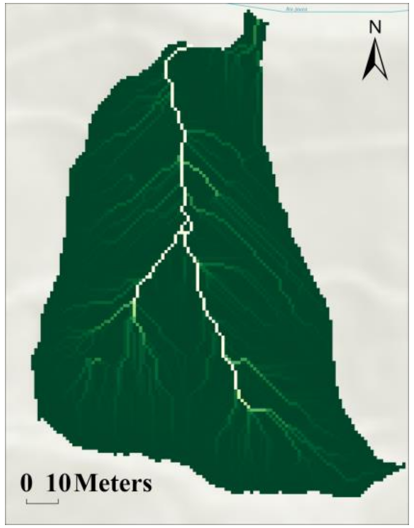


Antecedent Soil Moisture

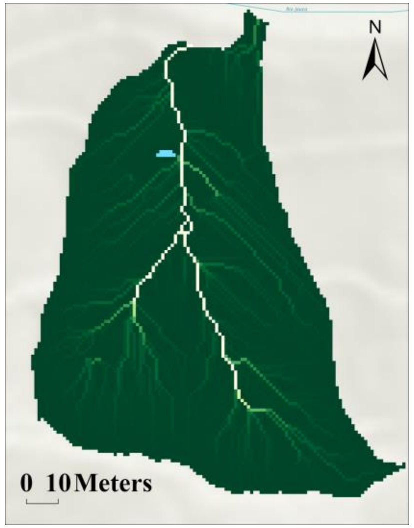


Spatial Distribution of Predicted Landslides over Time

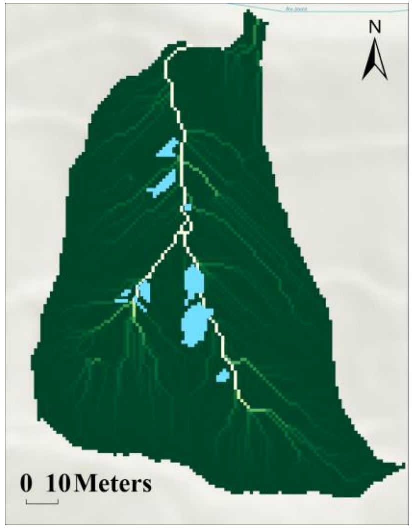
09/19/2017 at 12:00 a.m.



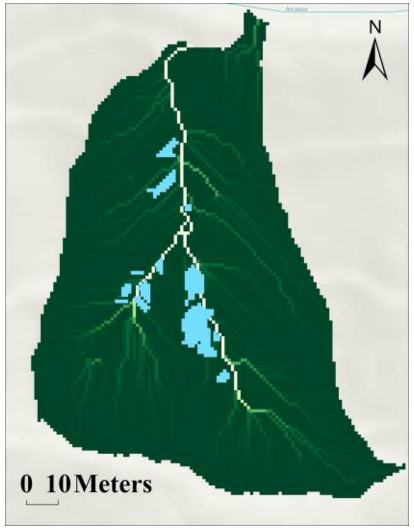
09/19/2017 at 10:00 p.m.



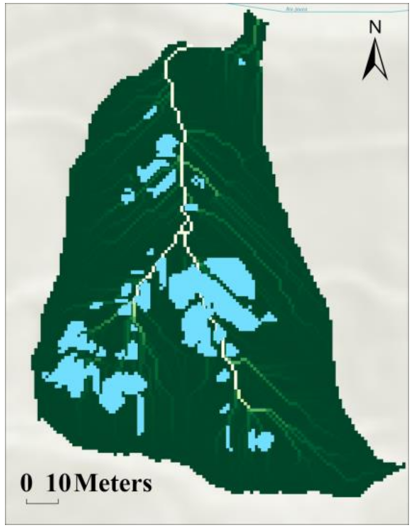
09/20/2017 at 03:00 a.m.



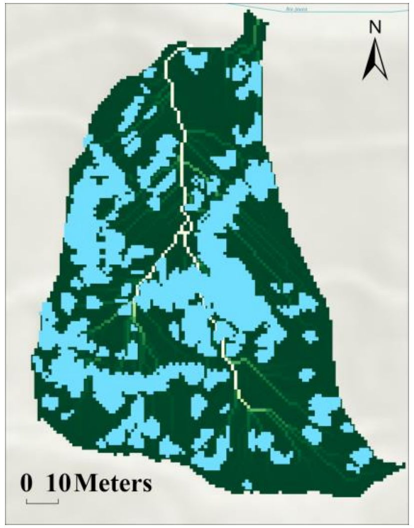
09/20/2017 at 06:00 a.m.



09/20/2017 at 11:00 a.m.



09/22/2017 at 12:00 a.m.



Flow Accumulation Area (m^2)

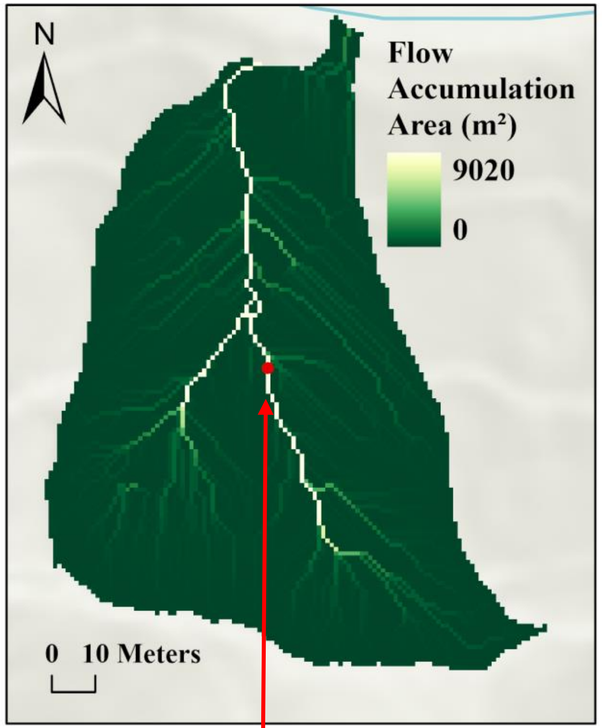
0 **9020**

🟦 **Predicted Landslides**

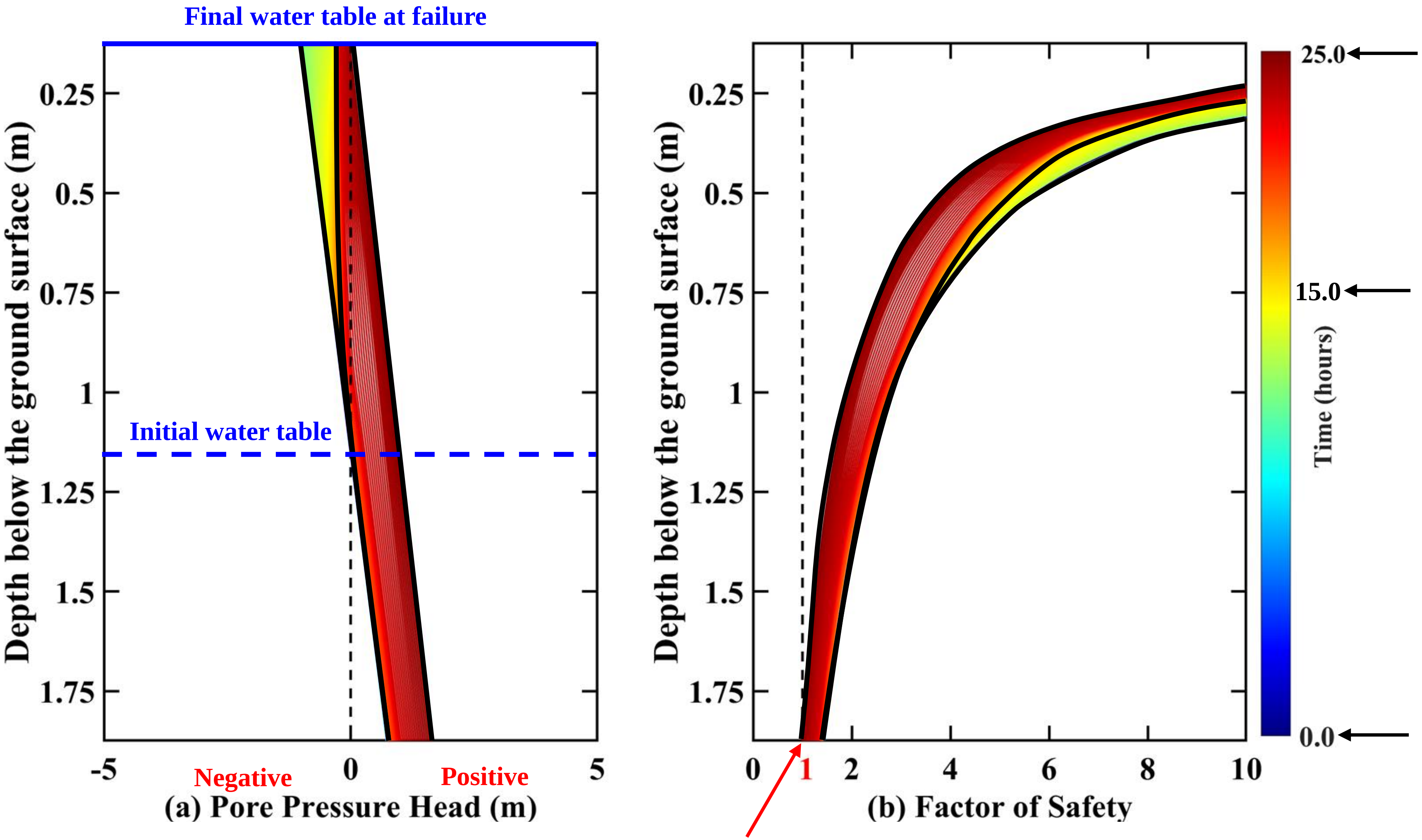
$c' = 20$ kPa, $\phi' = 37^{o}$
k_s decreasing with depth starting at 3e-06 m/sec at the surface

- **Bottom-up** failures are triggered **first** near the **valley bottoms**.
- When all bottom-up failures are triggered, **top-down** failures are triggered.

Example at Valley Bottom: Bottom-up Failure



Cell at a valley bottom
c' = 20 kPa; ϕ=37º

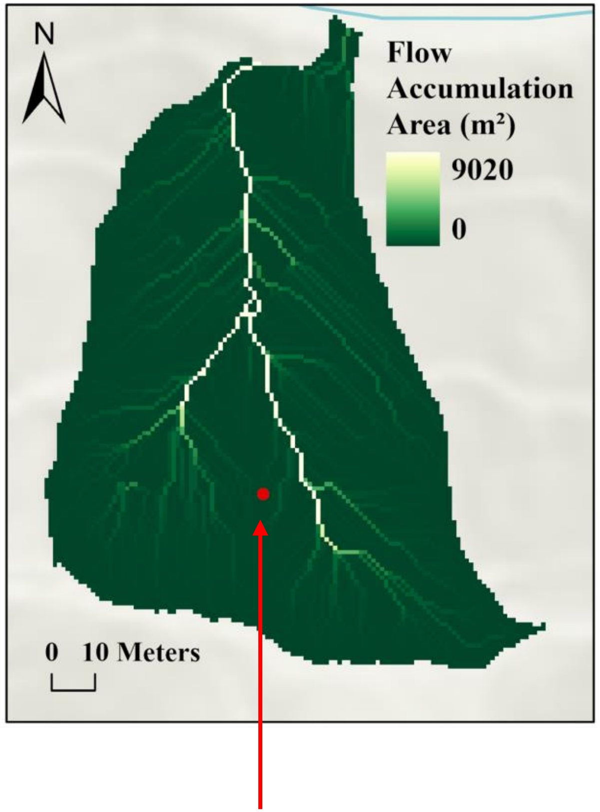


(a) Pore Pressure Head (m)

(b) Factor of Safety

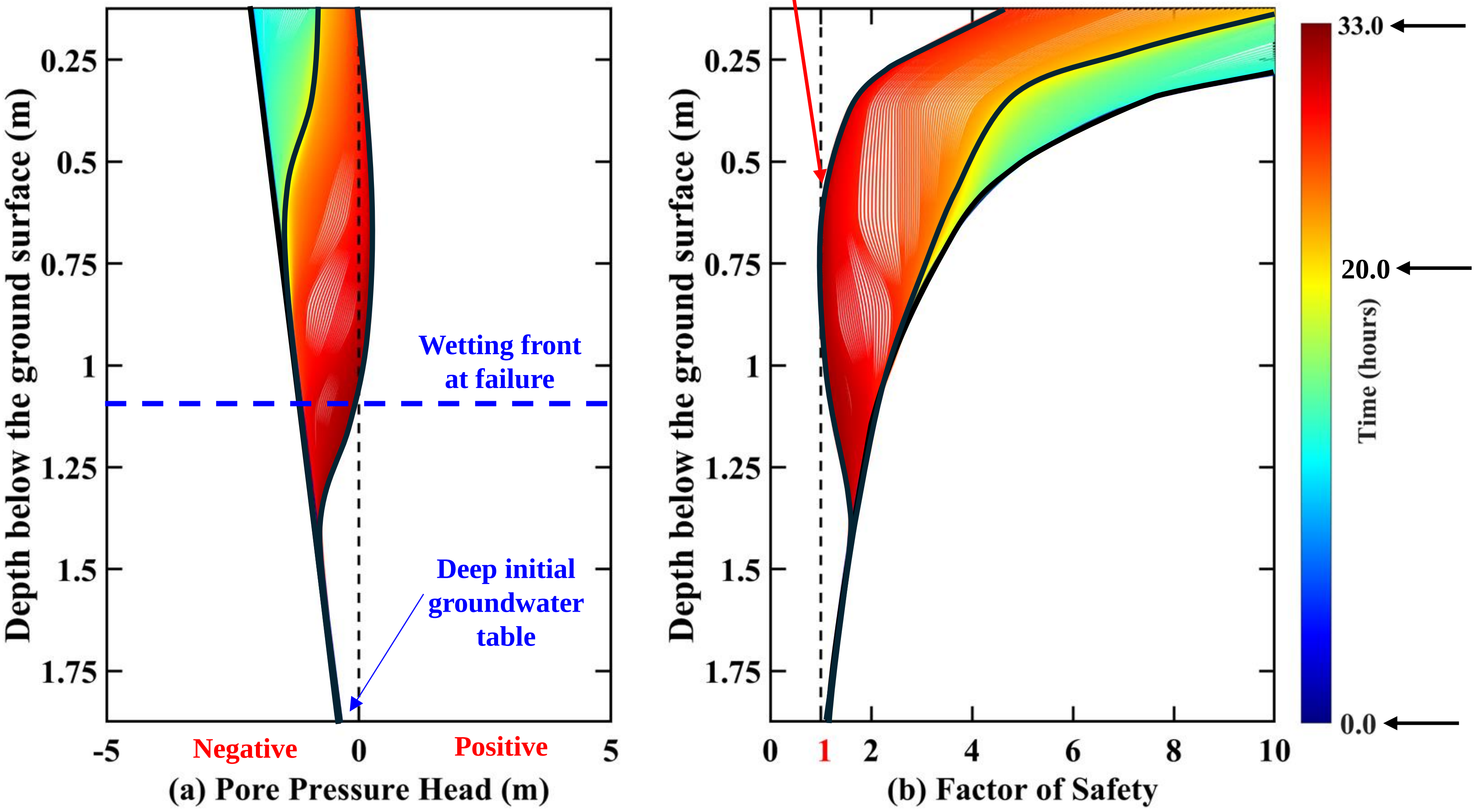
Failure!

Example at Ridge Top: Top-down Failure-Wetting Front



Cell near ridge top

c’ = 5 kPa; ϕ=37º

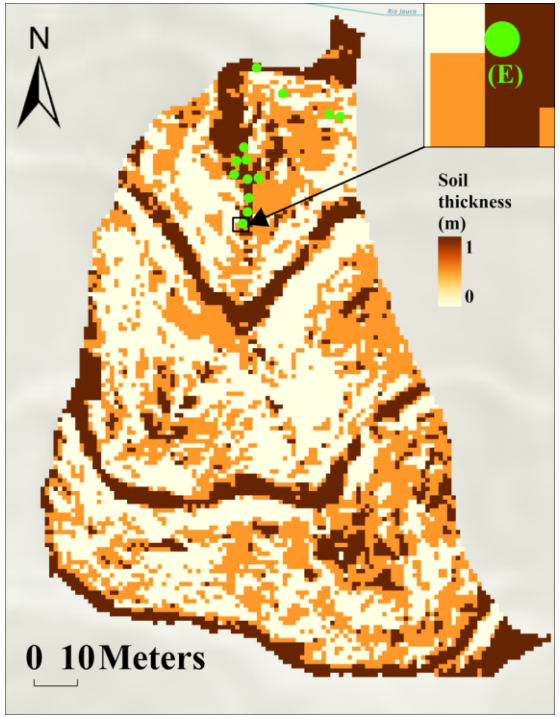


Failure!

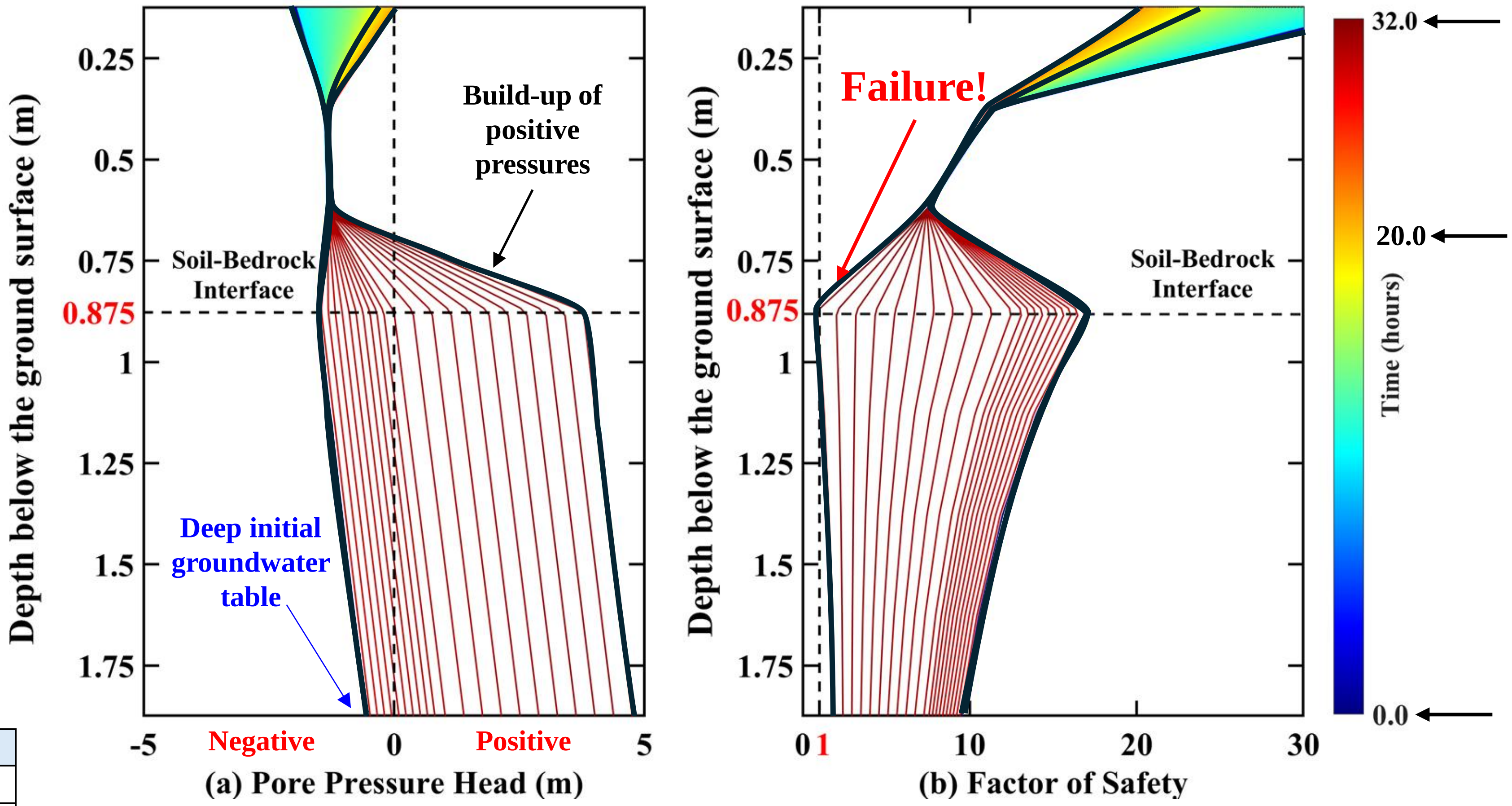
Wetting front at failure

Deep initial groundwater table

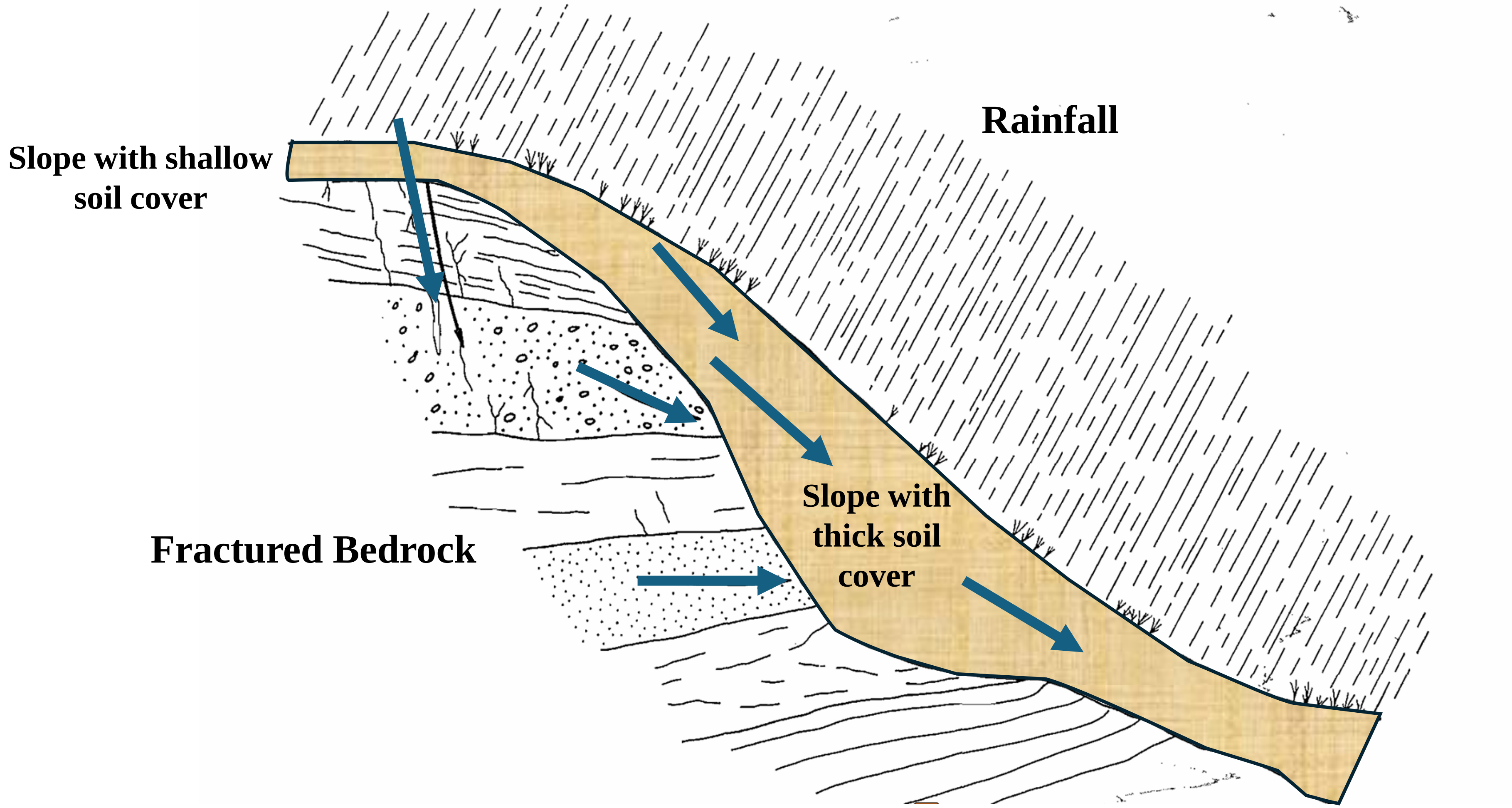
Example of Water Exfiltration from Fractured Bedrock



Material	Soil	Fractured Bedrock
c'	15 kPa	40 kPa
ϕ'	30º	60º
k_s	5e-09 m/s	5e-04 m/s



Water Exfiltration from Fractured Bedrock



(Johnson and Sitar, 1990)

Conclusions

- **Different failure mechanisms** can be triggered across the topography, influenced by slope geomorphic positions, shear strength, subsurface soil types, soil thickness, and bedrock properties.
- **Regional scale** landslide modeling is crucial for enhancing the **community resilience**.
- Advanced mechanistic regional predictive models can be **computationally demanding**.
- Understanding the importance of each of the model's input **parameters/features** is important to avoid compromises that can impact the **validity of the predictions**.