Regional Pseudo-3D Prediction of Rainfall-Induced Landslides in Utuado,Puerto Rico

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Predicting rainfall-induced landslides over large spatial scales is often limited by the simplifications introduced in the hydrological and slope stability models and the uncertainties in the knowledge of mechanical and hydrological properties of soils. Current mechanistic-based models for regional slope stability often make simplifications either on the geometry of the landslide (1D, 2D, 3D) or the pore water regime in an effort to increase computation efficiency. Further, a constant pore-water pressure coefficient (Ru) is commonly applied to the entire study area to represent a particular rainfall event. In this work, a pseudo-3D methodology is developed. The triggering of a landslide is based on an infinite slope stability model applied on a digital elevation model, where a 3D geometric projection is applied to produce 3D landslides with determined locations and sizes. Two hydrological models are coupled with the pseudo-3D slope stability model to develop the prediction methodology: (1) a simplified constant Ru applied over the entire study area and (2) a popular model TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model). TRIGRS simulates transient subsurface infiltration induced by a rainstorm in both the saturated and unsaturated zones. It produces pore water pressure profiles at each raster cell that vary with depth and time. TRIGRS is typically implemented in 1D slope stability models; however, in our analysis, we used the resulting pore water pressures in a pseudo-3D stability assessment. We apply both approaches to a 2.5 km^2 test area in Utuado, Puerto Rico underlain by granodiorite bedrock which was a hotspot for shallow landsliding during Hurricane Maria in 2017. The results of both models are compared to a mapped landslide area and volume inventory and significant differences are observed with regards to the size and location of predicted landslides. The use of Ru omits the variation in pore water pressures with depth, spatially and temporally, as well as the possibility of failures in the partially saturated zones. The results highlight the importance of spatial and temporal variation in pore water pressures induced by a rainstorm and the importance of having high-quality rainfall data and soil parameters for a better performance of the predictive models.

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Why is Landslide Prediction Necessary?

LANDSLIDE EARLY WARNING SYSTEM

EVOLVING LAND USE

CLIMATE CHANGE

COMMUNITY RESILIENCE

Features of Existing Models

1. Predictive Approach

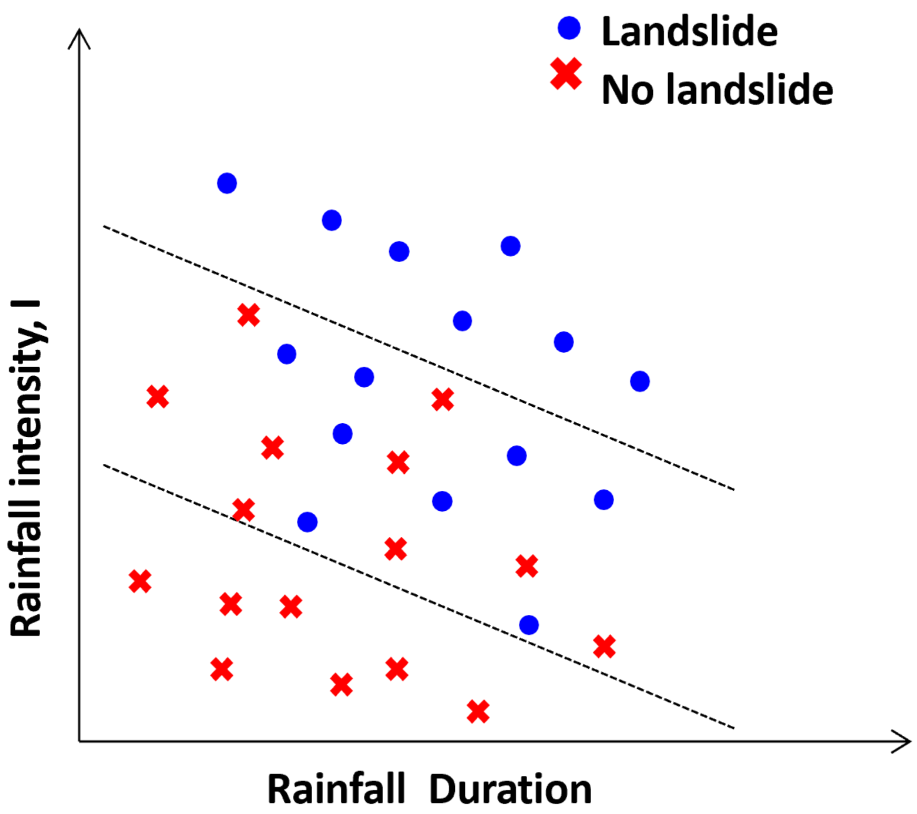
2. Size of the Study Area

3. Failure Criterion

4. Hydrological Model

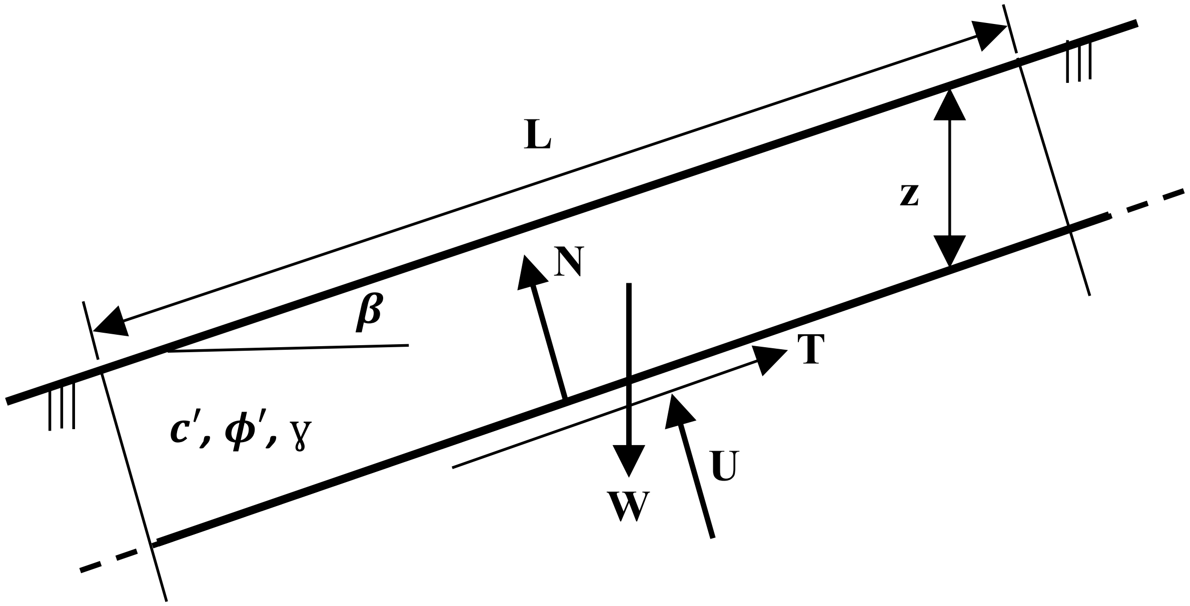
1. Predictive Approach

EMPIRICAL



Hong et al., 2018
Segoni et al. 2018
Dikshit et al. 2019

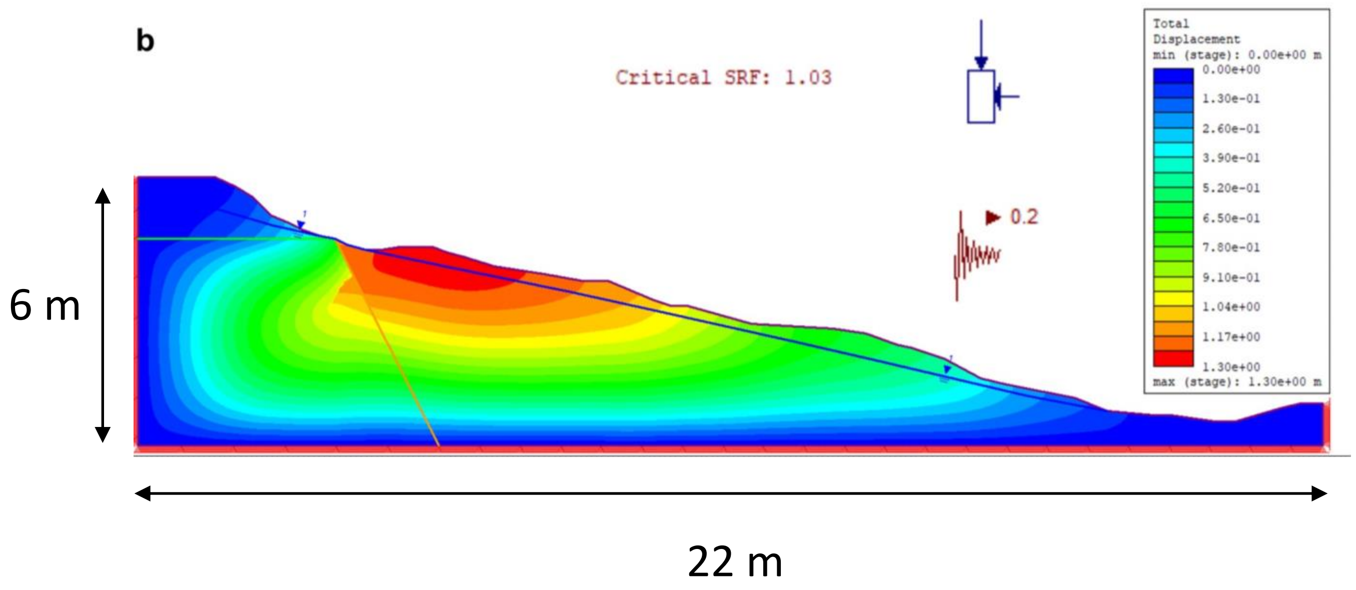
MECHANISTIC



Duncan et al., 2014

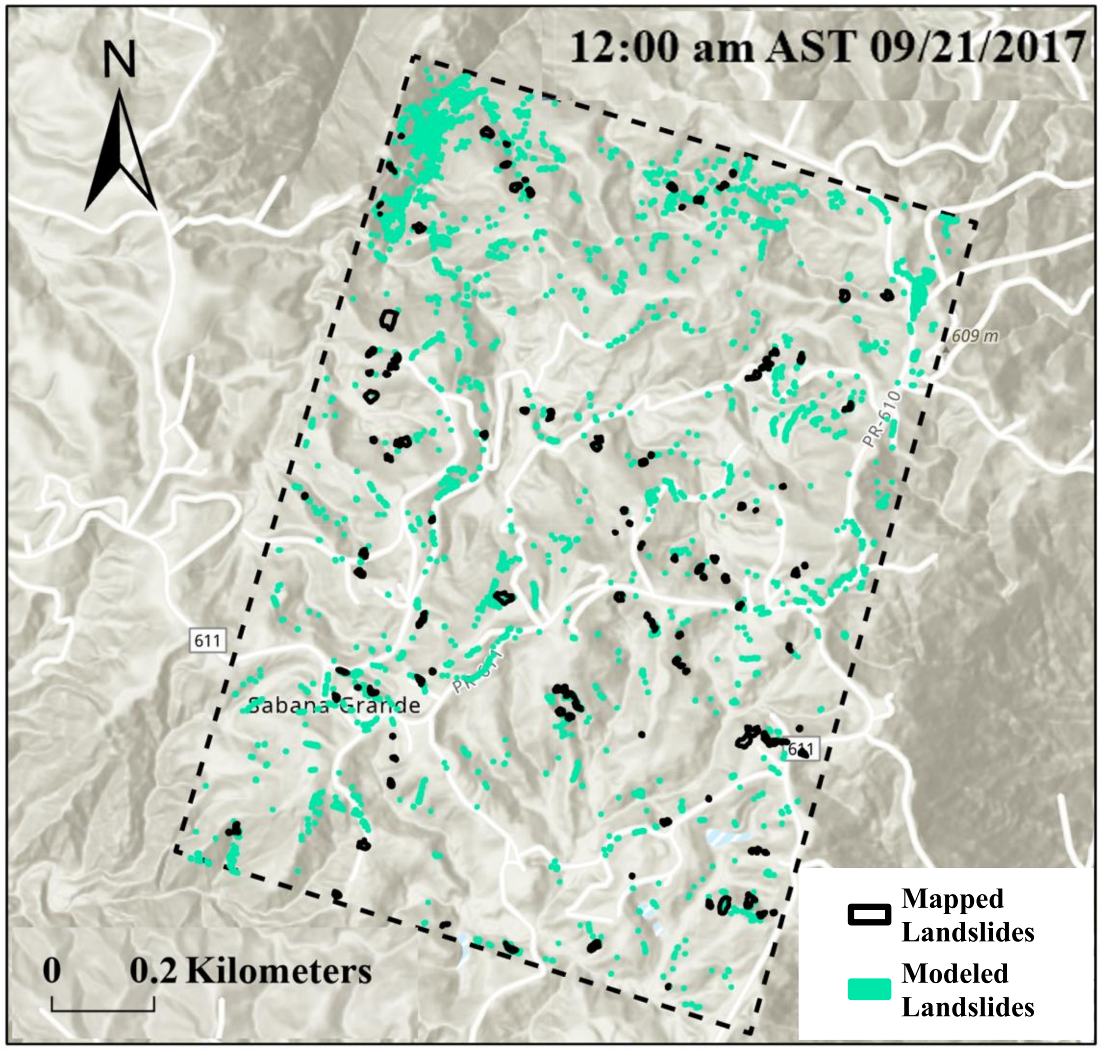
2. Size of the Study Area

SINGLE HILLSLOPE



Mebrahtu et al. (2018)

REGIONAL SCALE

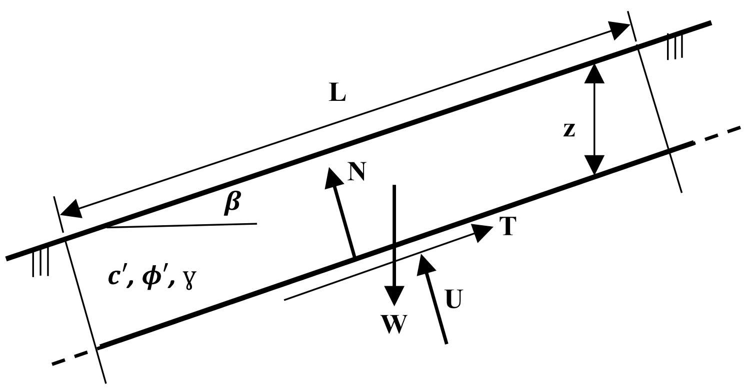


3. Failure Criterion

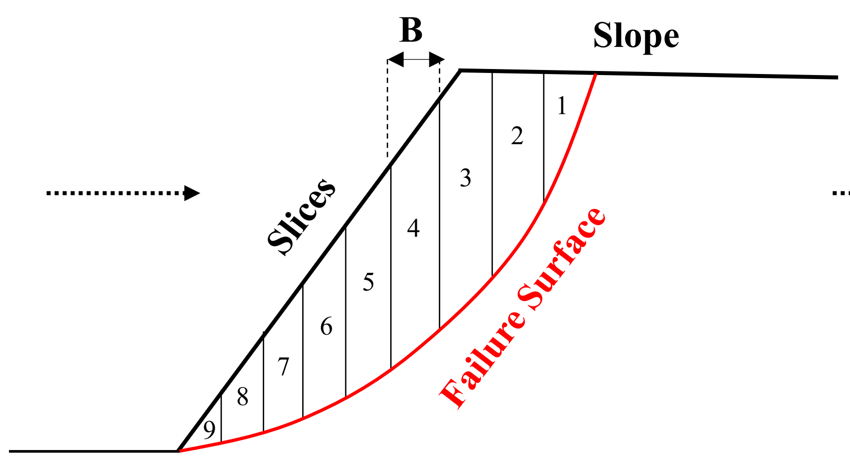
Increasing Geometric Accuracy

Increasing Complexity

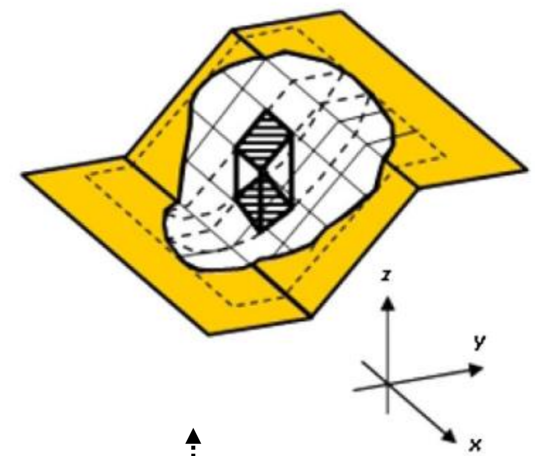
1-Dimensional



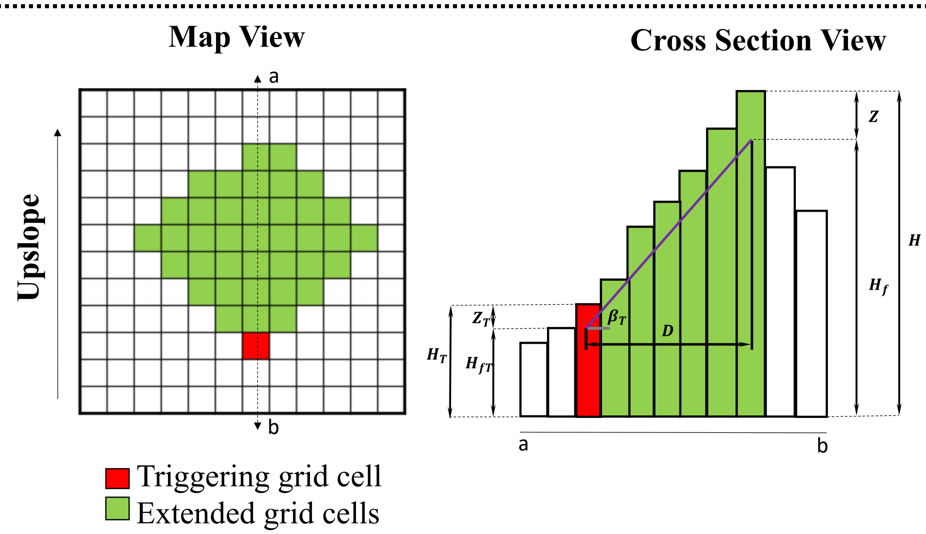
2-Dimensional



3-Dimensional

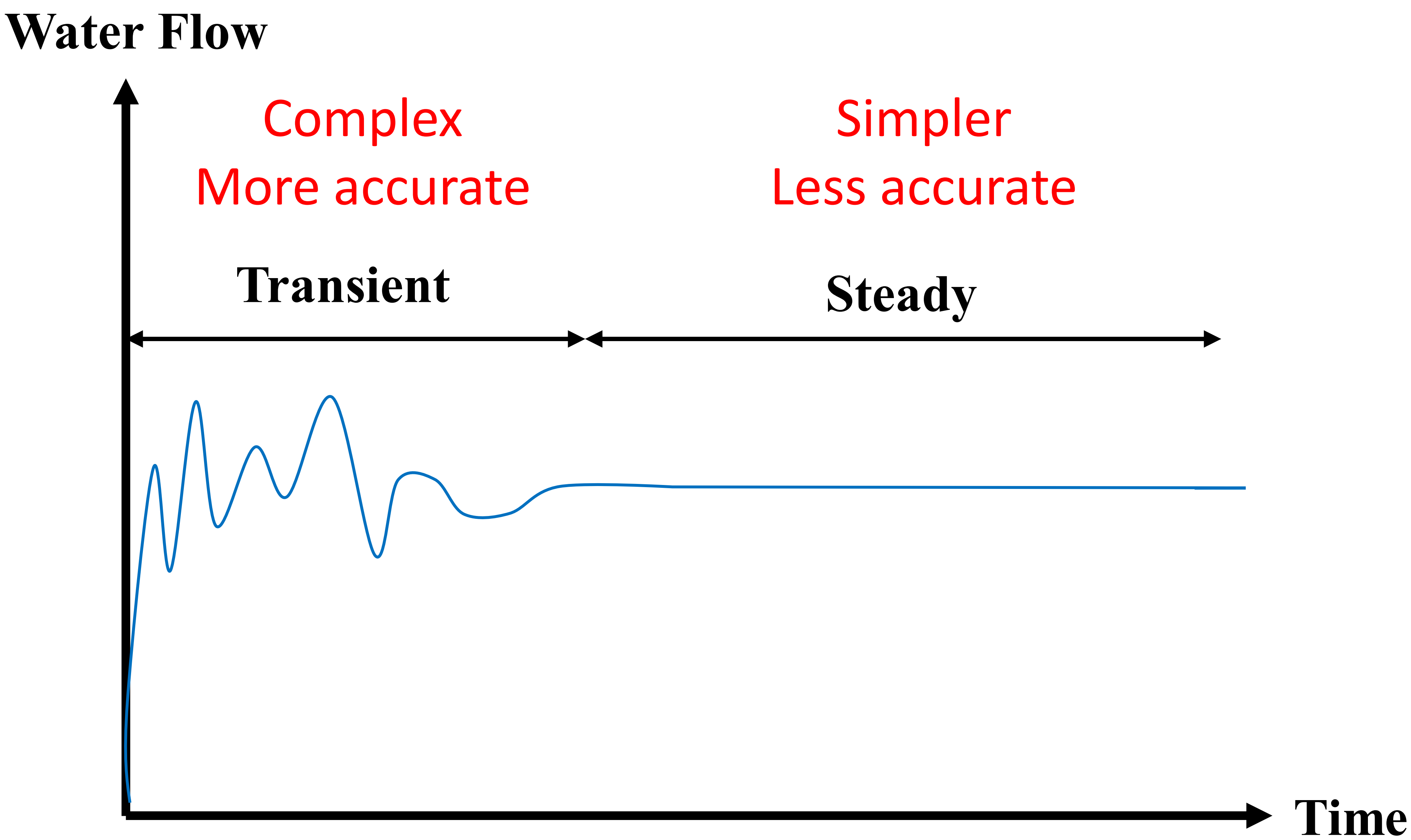


Pseudo -3-Dimensional



Gong et al., 2023

4. Hydrological Model



Mechanistic, Regional Modeling of Rainfall-Induced Landslides using a Pseudo-3D and Transient Infiltration Models

INVERSION

Mapped Landslides Inventory

+

Previous rainfall event

Back-calculated Shear Strengths

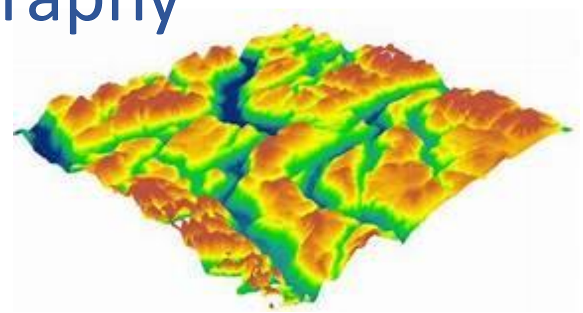
+

FORWARD MODELLING

New rainfall event

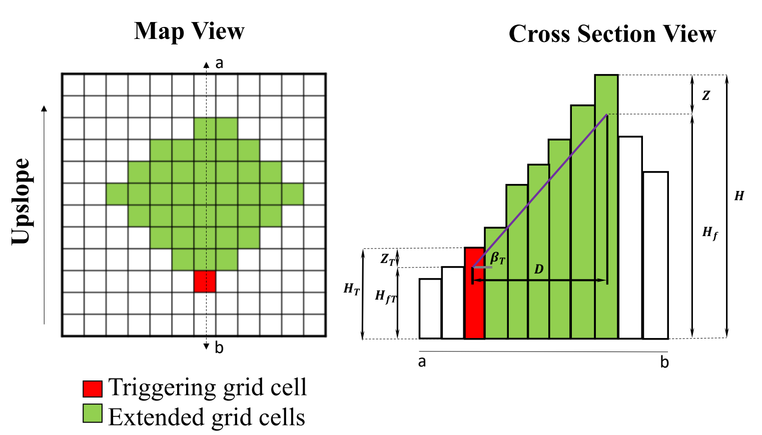
+

Topography



+

Our model

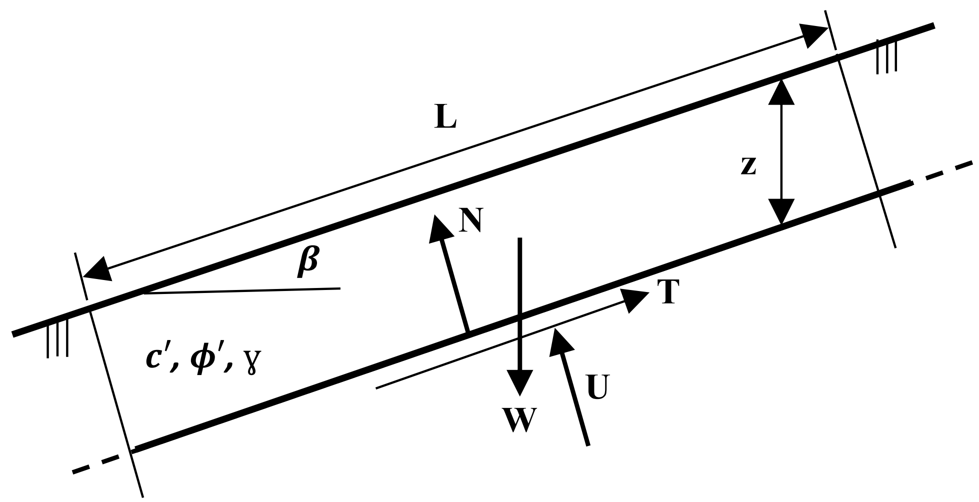


Predicted Landslides

Pseudo-3D Slope Stability

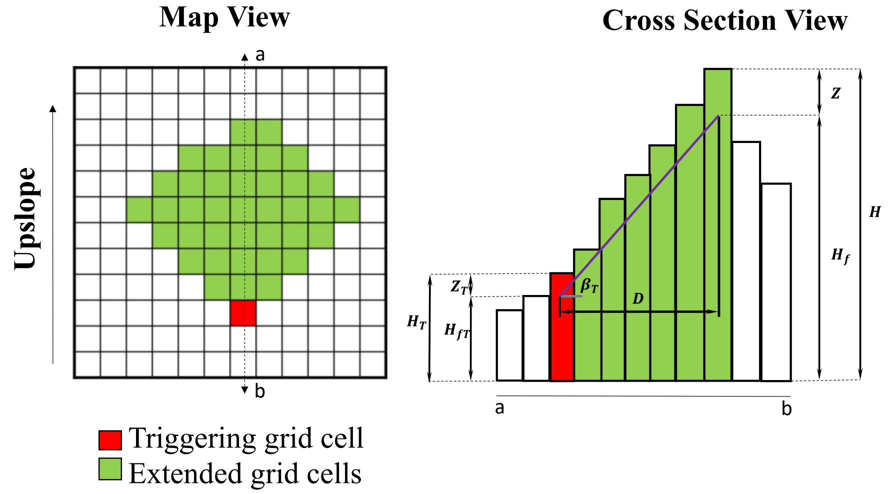
Two main steps:

1. 1D Triggering of Landslides ➔ Identify Triggering Cells

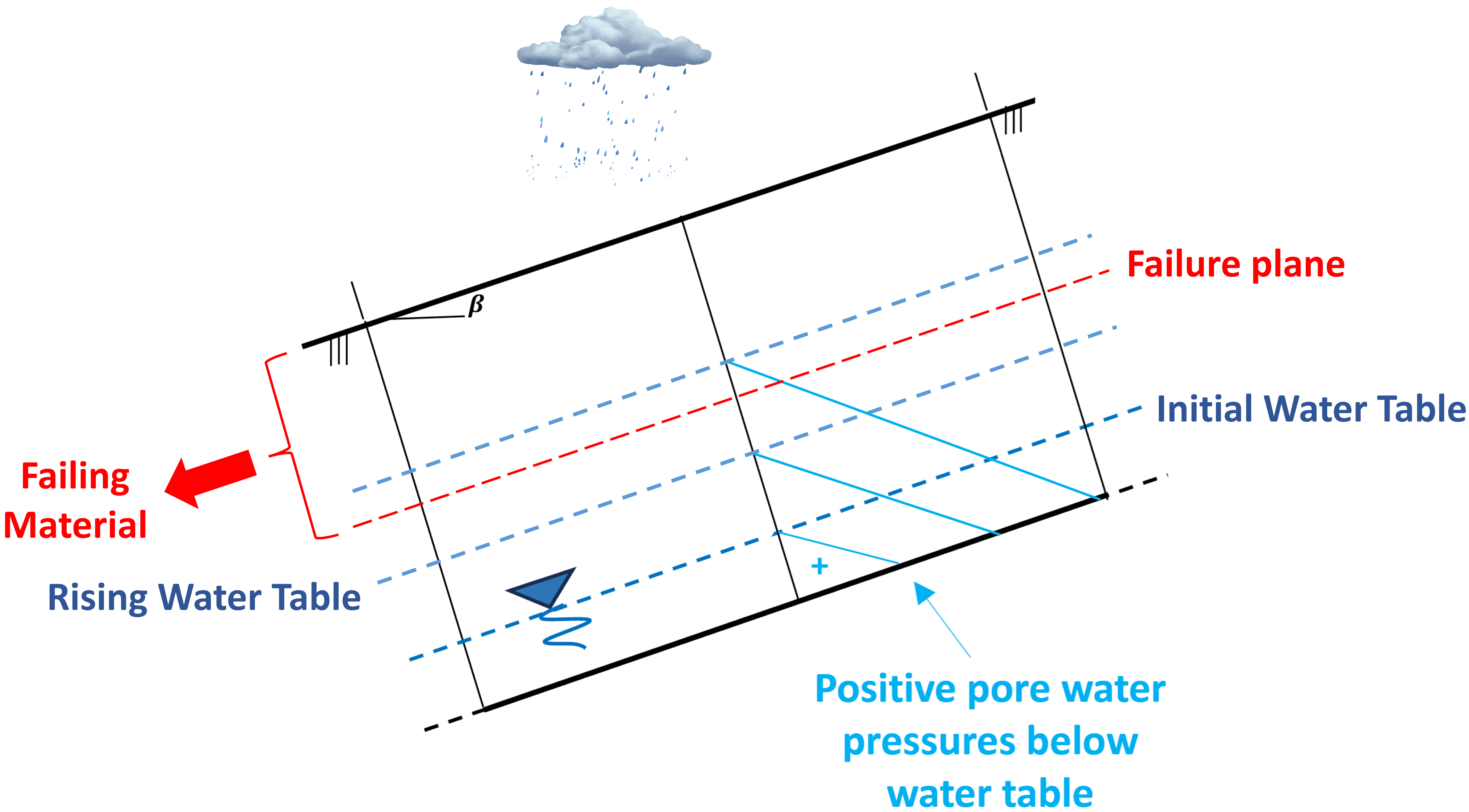


Two Failure Mechanisms:
- **Bottom-Up Failure Mechanism**
- **Top-Down Failure Mechanism**

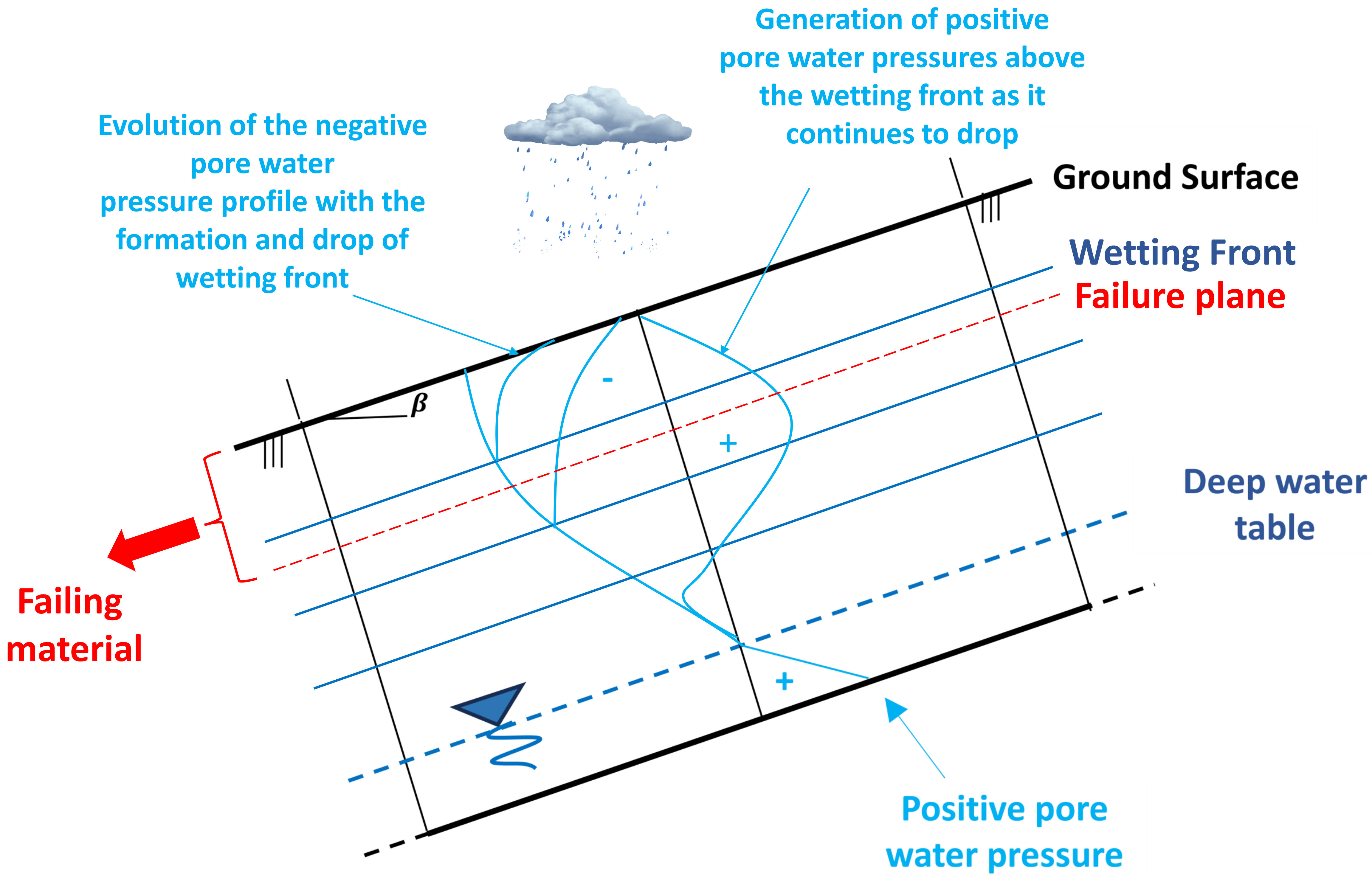
2. Formation of 3D Landslides by a Geometric Projection



Bottom-Up Failure Mechanism



Top-Down Failure Mechanism



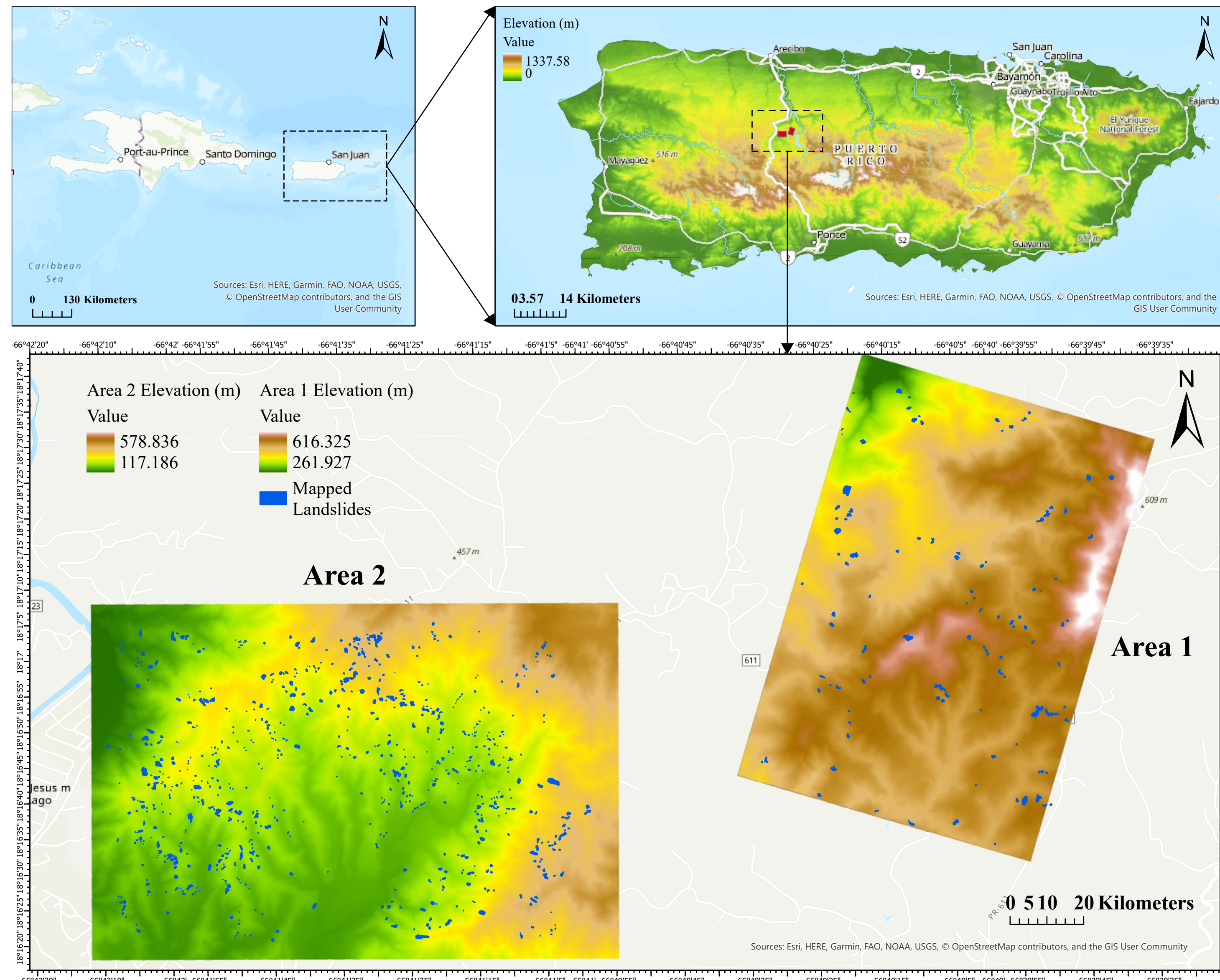
Mechanistic Models: Coupled Hydrological and Pseudo-3D Slope Stability Models

1. Steady Flow-Pseudo-3D Model	2. Transient Flow-Pseudo-3D Model
Simple hydrological model, pore water pressure coefficients (R_u)	**Transient Rainfall Infiltration hydrological model (TRIGRS)**
Pore water pressure coefficient (R_u) **is constant spatially and with depth**	**Pore water pressures are variable spatially and with depth**
Steady flow in the saturated zone only	**Transient** infiltration in the saturated & unsaturated zones
Does not capture time dependency	**Captures** time dependency
Outputs: well-defined landslides with areas, volumes, thicknesses, and locations	Outputs: well-defined landslides with areas, volumes, thicknesses, locations, and **time of failure**

Model Implementation in Puerto Rico, Hurricane Maria, 2017

Utuado, Caonillas Lake; Lat: +18.26701, Lon: -66.66009667; 2017.11.02 (GEER report)

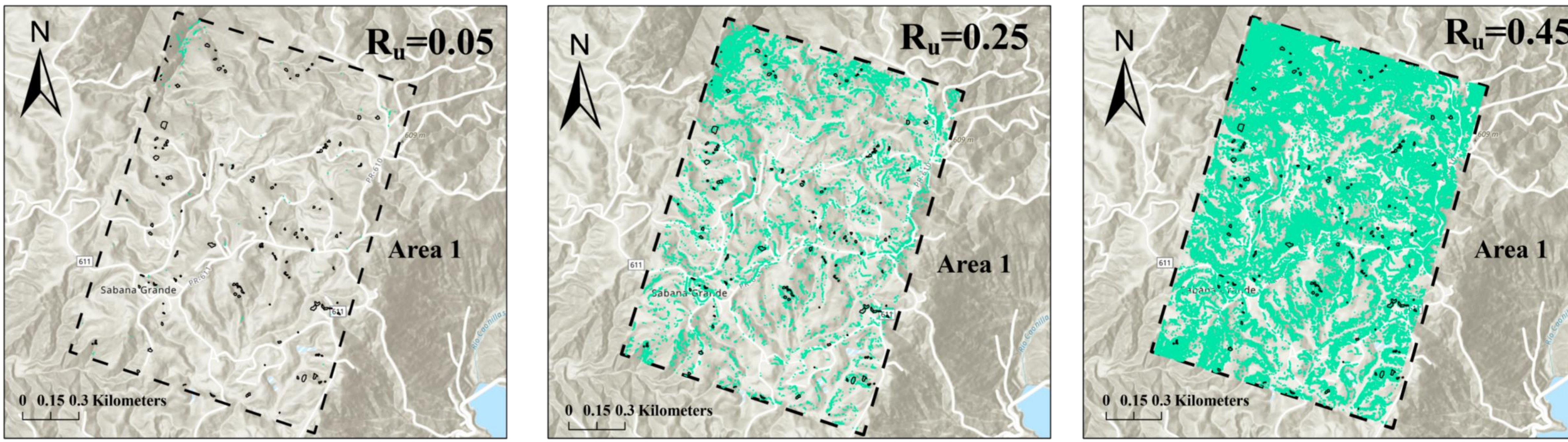
Canóvanas, PR-186; Lat: +18.270945, Lon: - 65.86504667; 2017.11.05 (GEER report)



1m-resolution DEM (U.S. Geological Survey, 2017)
Mapped landslides inventory (U.S. Geological Survey, 2020)

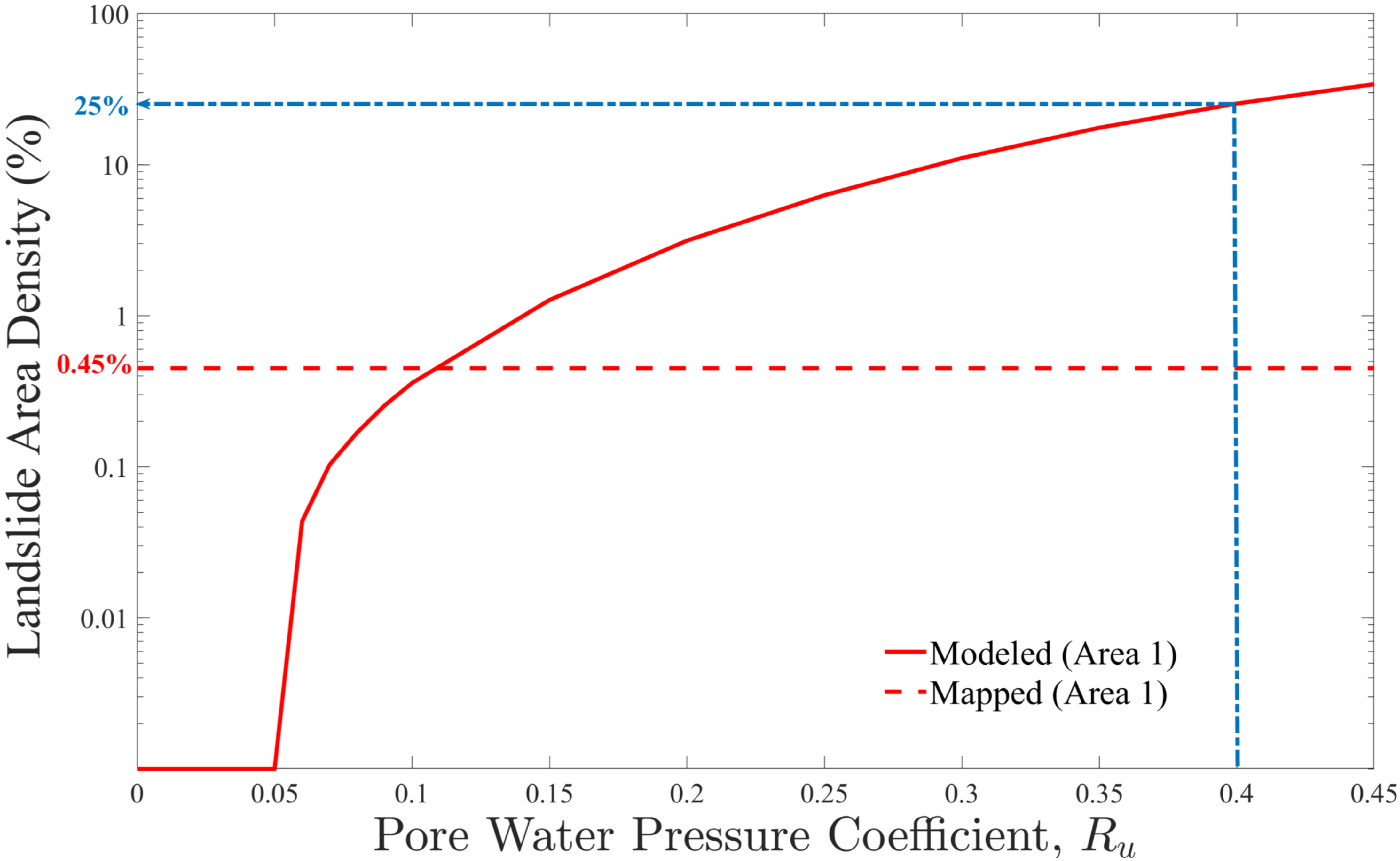
Steady-Flow-Pseudo-3D Model Results

$c' = 14$ kPa, $\phi' = 57°$



The model overpredicts landslides.
The mapped and modeled landslides do not match in terms of location, areas, frequency, and landslide area density.

Steady-Flow-Pseudo-3D Model Results

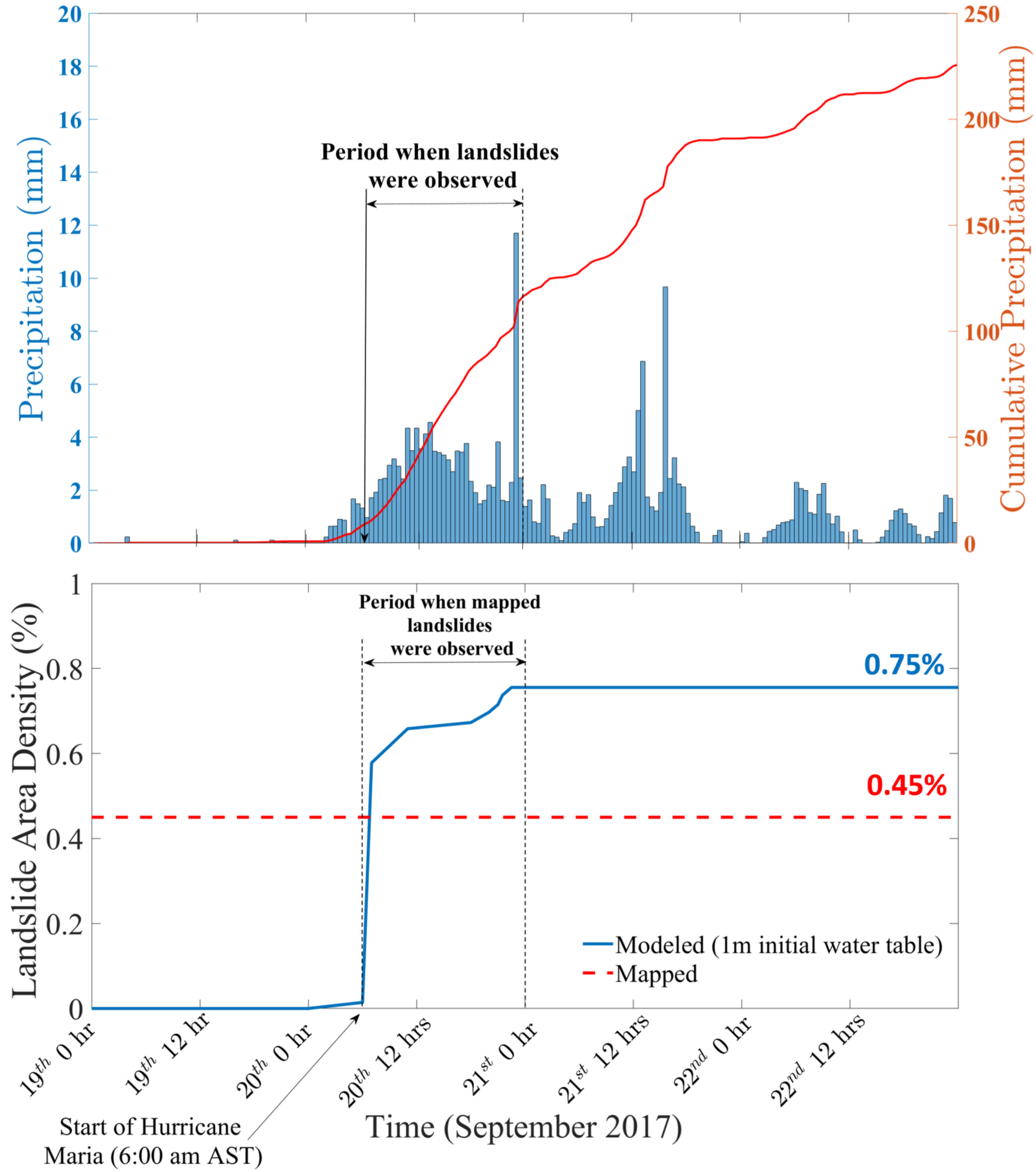


Log scale !!

The model highly overpredicts landslides!

Transient-Flow-Pseudo-3D Model Preliminary Results

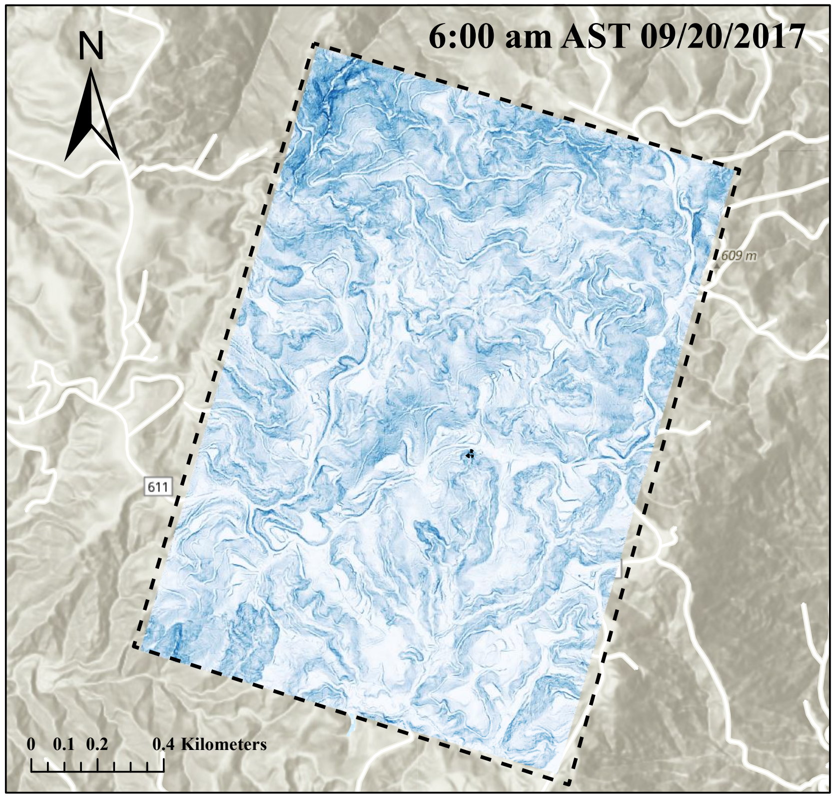
The model was able to capture the timing of failure successfully!

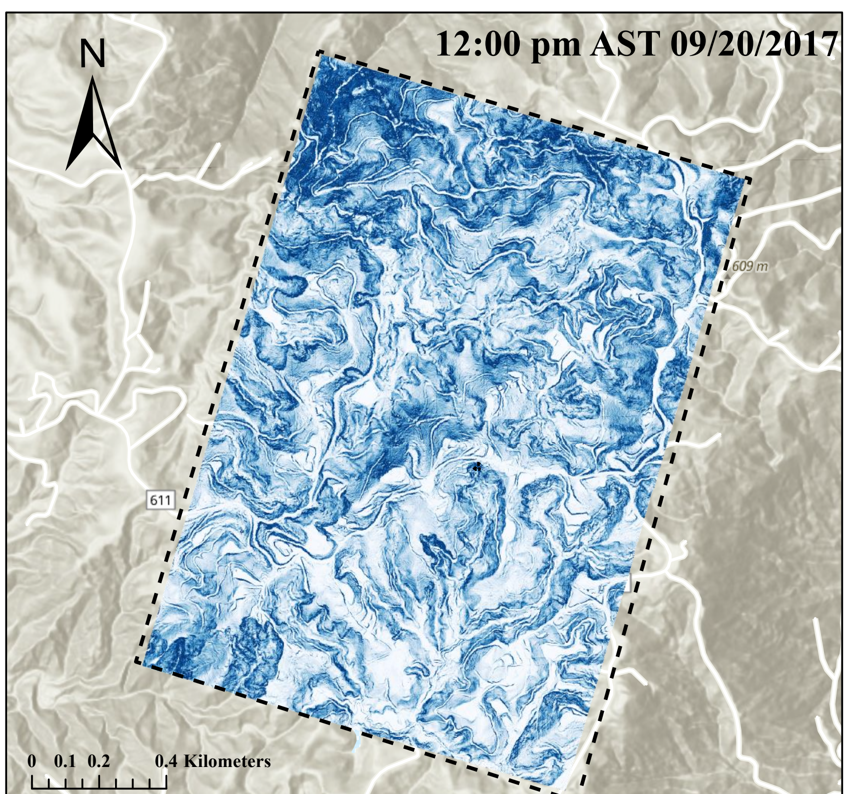


Both figures are sharing same x-axis!

Variation in Pore Water Pressures with Time

Start of Hurricane Maria





Pressure head (m)

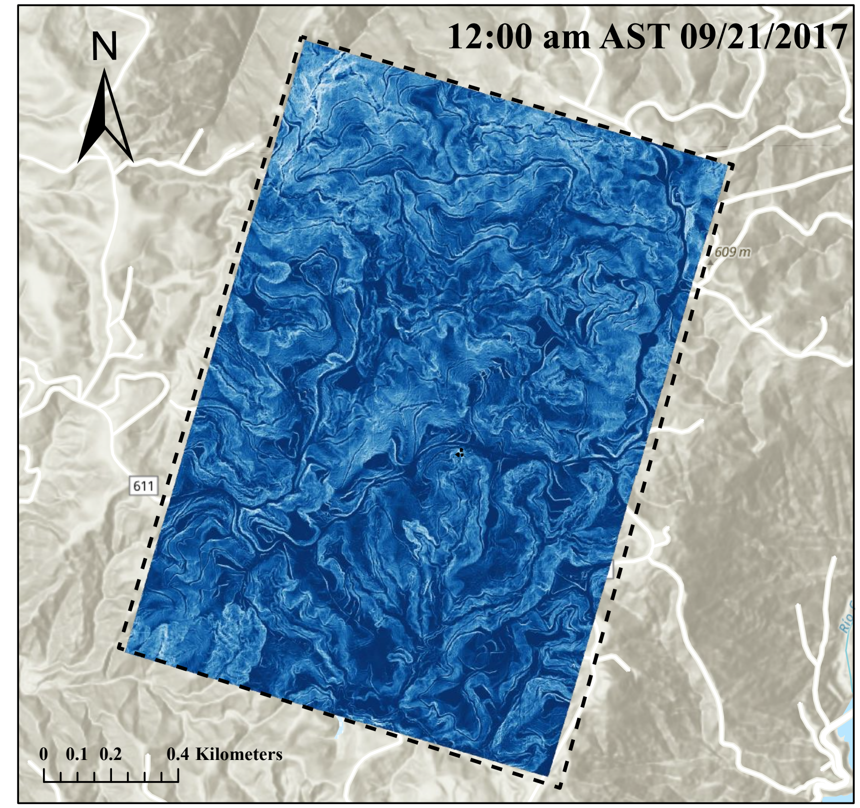
Value

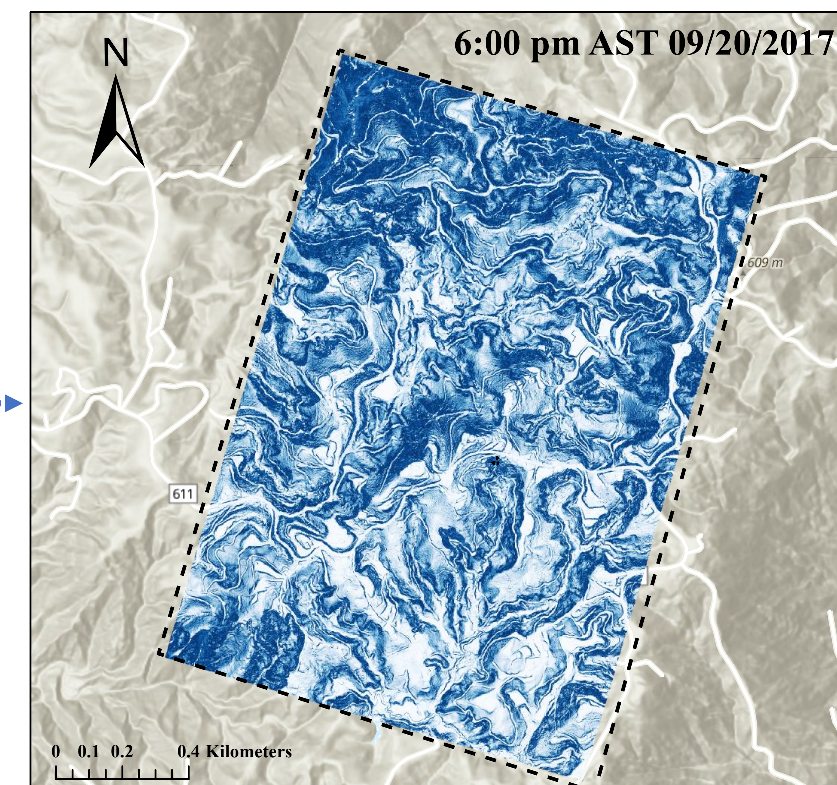
3

-1

Increase in the pore water pressures with time!

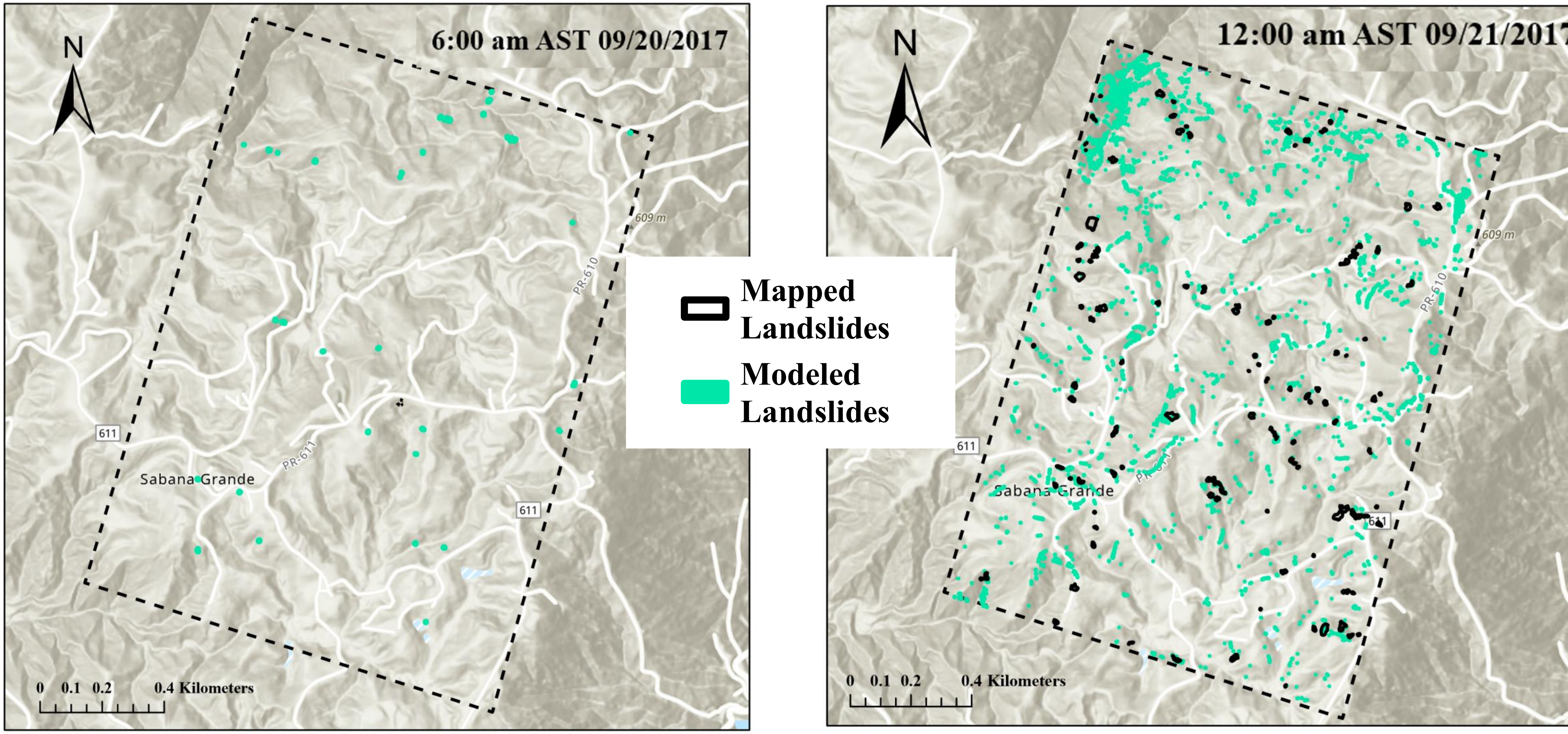
End of Hurricane Maria





Transient-Flow-Pseudo-3D Model Preliminary Results

Start of Hurricane Maria | **End of Hurricane Maria**



$c' = 14$ kPa, $\phi' = 57°$

The model outperformed the steady flow model; however, we still have some overprediction given the assumption of "Constant strength spatially"

Conclusions

- Our current model combines the following key features:
  - Mechanistic, pseudo-3D slope stability
  - Transient infiltration with potential failures in both the saturated and unsaturated zones
  - Regional scale stability assessment with ability to invert previous events and model future scenarios.
- Model predicts well-defined (i.e., locations, areas, volumes, depths, geometry, and timing of failure) individual rainfall-induced landslides on a regional scale.
- The transient flow model outperformed the steady flow model by reducing the overprediction of landslides significantly and by estimating the timing of failure for each landslide.
- Use of a constant shear strength throughout the region results in landslide overprediction.

THANK YOU!

ANY QUESTION?

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