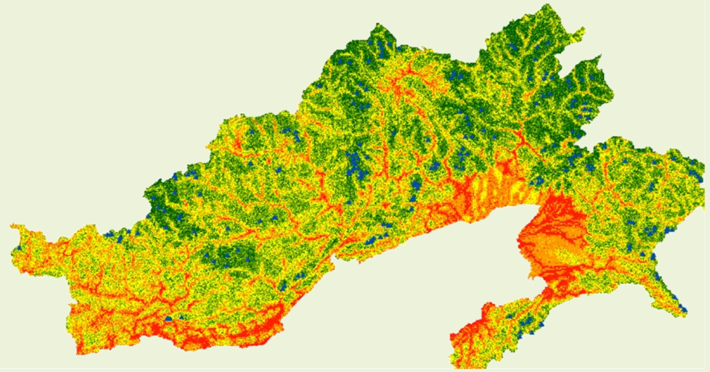
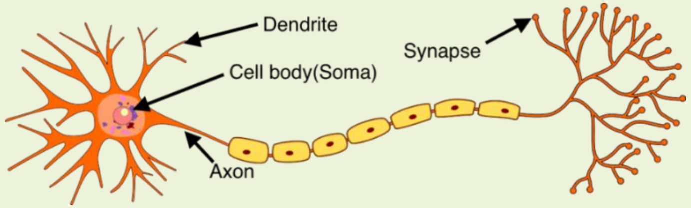
International Lecture Program

Center for Disaster Management Informatics Research

Ehime University, Japan



Rainfall-Induced Landslide Susceptibility of Arunachal Pradesh and Sikkim: Synergizing Remote Sensing and Machine Learning



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Geotechnical Engineering Division
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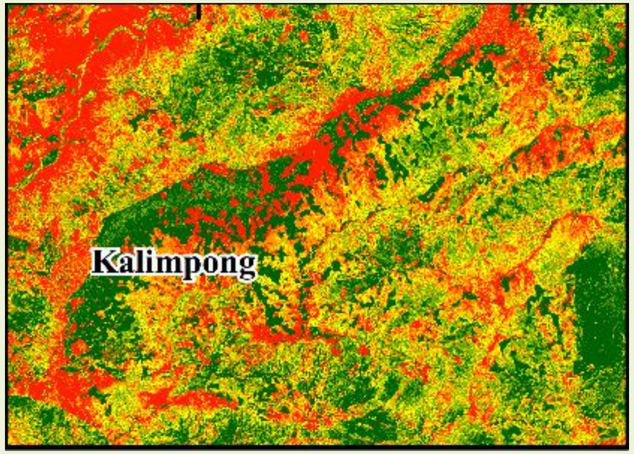


My Academic Journey

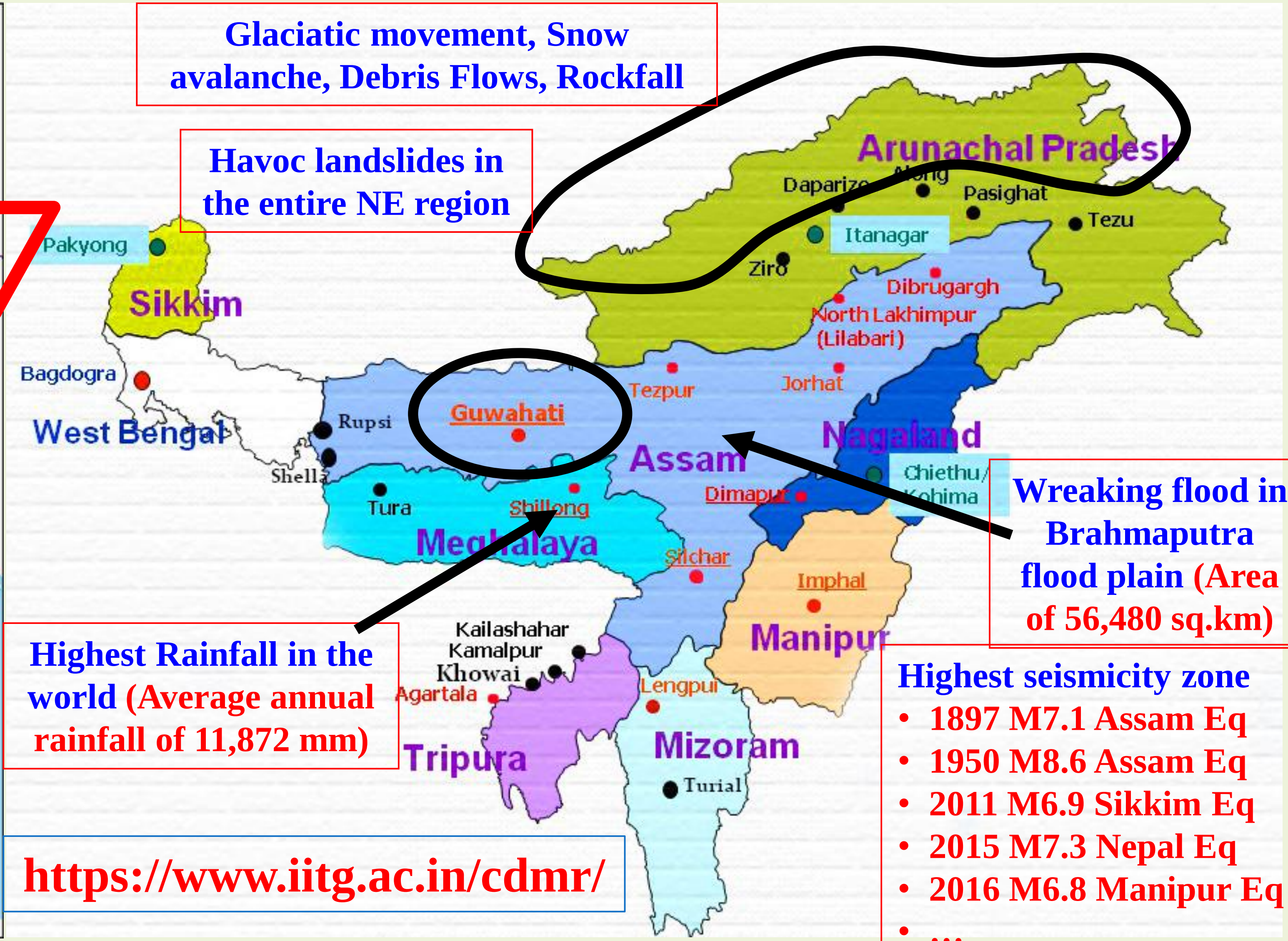
- Bachelor of Engineering (B.E.)
  - ❖ Jadavpur University, Kolkata
- Master of Technology (M.Tech.)
- Doctor of Philosophy (Ph.D.)
  - ❖ Indian Institute of Technology Kanpur

    - **Beams on elastic foundations (unreinforced and reinforced)**
    - **Beams on viscoelastic foundations (unreinforced and reinforced)**
    - **Lumped parameter modelling (4-parameter Burger model) in reinforced foundation beds**
    - **Inverse analysis and optimization to assess parameters of Burger model**
- Post-Doctoral Research (PDF)
  - ❖ Structural and Geotechnical Laboratory, University of Molise, Italy

Università degli Studi del Molise

    - **Structural health monitoring of full-scale instrumented contiguous pile retaining wall**
    - **Finite element modelling to assess ambient vibration response of full-scale retaining wall**
- Joined IIT Guwahati in 2011 (Assistant Prof.) and promoted in 2019 (Associate Prof.)

Geographical Location of IIT Guwahati in NE India



Glaciatic movement, Snow avalanche, Debris Flows, Rockfall

Havoc landslides in the entire NE region

Wreaking flood in Brahmaputra flood plain (Area of 56,480 sq.km)

Highest Rainfall in the world (Average annual rainfall of 11,872 mm)

https://www.iitg.ac.in/cdmr/

Highest seismicity zone
- 1897 M7.1 Assam Eq
- 1950 M8.6 Assam Eq
- 2011 M6.9 Sikkim Eq
- 2015 M7.3 Nepal Eq
- 2016 M6.8 Manipur Eq
- …

Probabilistic and Uncertainty Analyses

Soil Mechanics and Dynamics

Soft Soil Improvement using PVDs

Earthquake Geotechnics SHA/GRA/LA

Geophysical Investigations

Cold Regions

Transportation Geotechnics

Earthen Dams, Ash Dykes and Embankments

Foundations on Slopes

Pile-Soil-Structure Interaction

Granular Collapse and Debris Flow

Shallow and Deep Foundations

Glaciolacustrine Soils and Varved Clays

AI/ML in Geotechnics

Rainfall Induced Landslides

Seismicity Induced Landslides

Slope Stabilization and Landslide Mitigation

Reservoir Induced Seismicity

Ground Improvement

Computational Geotechnics

Experimental Geotechnics

Special Foundations

Geosynthetic Engineering and Applications

Reinforced Soil Structures

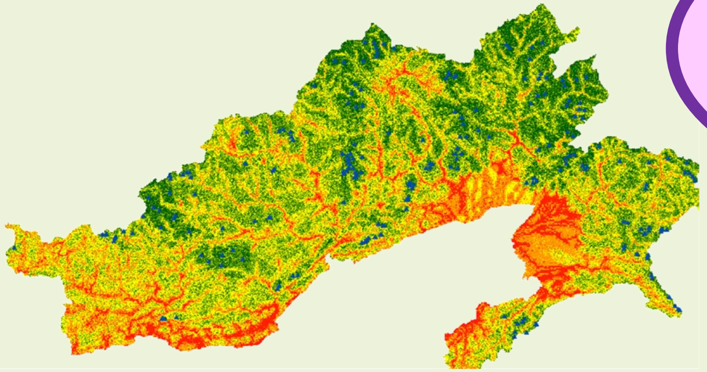
Retention Systems

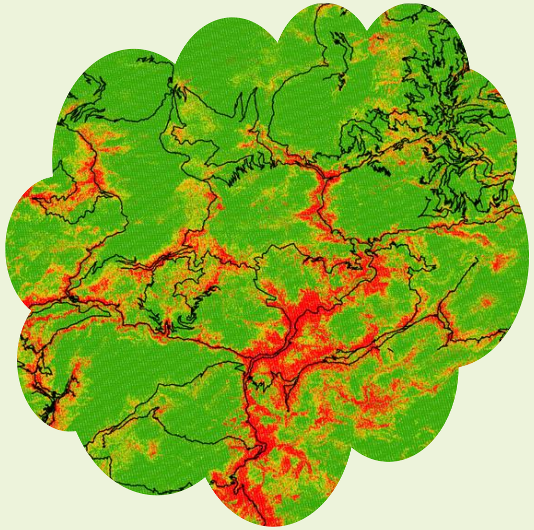
Rockslopes and Rockfalls

Rainfall-Induced Landslide Susceptibility of Arunachal Pradesh and Sikkim: Synergizing Remote Sensing and Machine Learning

Rainfall Induced Landslides ⟺ AI/ML in Geotechnics

Landslide Susceptibility Mapping

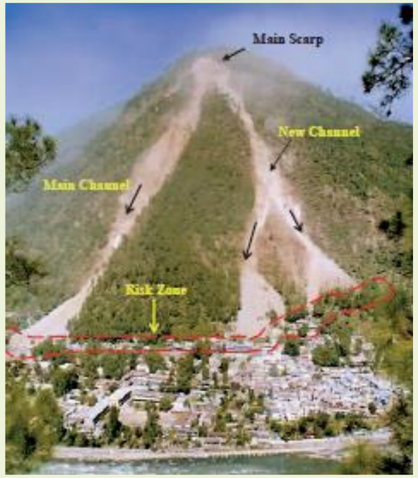




Commemorating Some Rainfall-Induced Landslides in India

Kohima Landslide (Nagaland)	17 August 1993	500 people died, 200 houses destroyed; Damage to 5 km road stretch
Leh landslide (Kashmir)	6 August 2010	145 killed, more than 2500 people affected and became homeless
Malin landslide (Maharashtra)	30 July 2014	151 people died, more than 100 were missing
Kuwari landslide (Uttarakhand)	10 March 2018	More than 400 people died, 106 houses perished
Pettimudi landslide (Kerala)	6 August 2020	80 people died, and many casualties occurred
Tupul landslide (Manipur)	30 June 2022	30 Indian Army personnel and 31 civilians were among the deceased
Wayanad Landslide (Kerala)	30 July 2024	254 fatalities, 397 injuries and 118 people missing
Dharali Landslide (Uttarakhand)	5 August 2025	70 people dead (may be understatement), severe damage to properties

Commemorating Some Rainfall-Induced Landslides in India



Varunavat Parvat Landslide, Uttarkashi, Uttarakhand, 2003

Malegaon Mudslide, Pune, Maharashtra, 2014

Sonitpur Mudslide, Assam, 2011

Raj Bhawan Landslide, Guwahati, Assam, 2020

Banderdewa Mudslide, Arunachal Pradesh, 2013

Landslide opposite to IIT Guwahati, Assam, 2020

Mangan, Sikkim, 2024

Important Terminologies in Landslide Assessment Studies

Spatial probability

Which

Where

Predisposing factors
&
Landslide inventory

Susceptibility

How much is the Hazard

When

Frequency of occurrence

Temporal probability

Risk

Risk = H × E × V

What are the Consequences

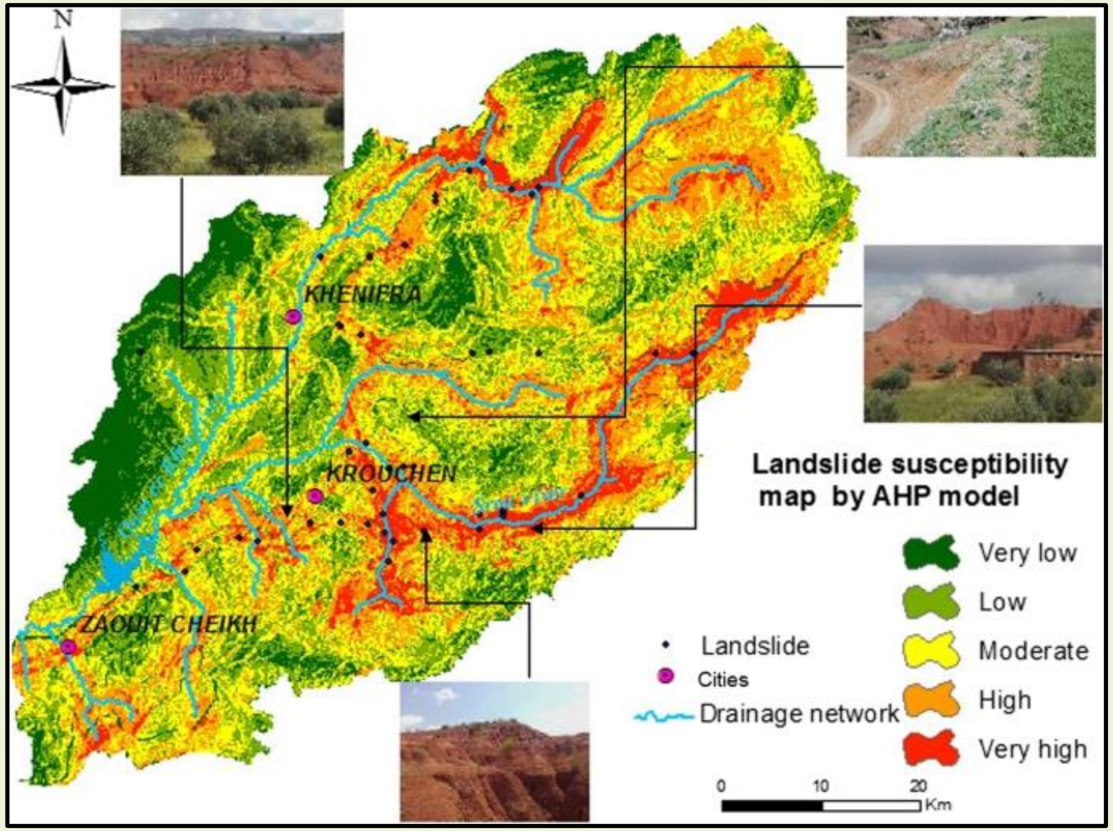
Exposure of elements at risk

Vulnerability

Source: The IAEG Commission on Landslides and other Mass-Movements

Landslide Susceptibility Mapping (LSM)

- **Landslide susceptibility**
  - ❖ Likelihood of a landslide occurrence across a given geographic area
- **Landslide susceptibility mapping (LSM)**
  - ❖ Aid in forecasting of landslide occurrence
- **Aim of landslide susceptibility mapping**
  - ❖ Understanding the potential risks associated with landslides in a particular region
  - ❖ Support decision-making in land use planning, engineering design and emergency management
  - ❖ Decrease the landslide disaster potential



Pham *et al*. (2017)

Landslide Susceptibility Assessment Methods

Qualitative Methods

- Involve **visual interpretation and expert judgment of the features of the terrain** to identify areas that are susceptible to landslides
- **Used for preliminary assessment (Das et al., 2011; Theiry et al., 2014)**

▪ **Expert Opinion**
▪ **Field Mapping**
▪ **Photo-interpretation**

Quantitative Methods

- Involve **use of statistical and mathematical models to map the relationships between landslide occurrence and various terrain attributes (Pardeshi et al., 2013; Marrapu & Jakka, 2014)**

▪ **Deterministic Approach**
▪ **Geological Approach**
▪ **Statistical Approach**
▪ **Machine Learning Approach**
▪ **Hybrid Approach**

Landslide Susceptibility Assessment Approaches

Deterministic Approach

- Traditional, analytical approach that relies on mathematical equations to determine the stability of slopes **(Singh et al., 2016; Das et al., 2020; Sarkar et al., 2020)**

↓

- **Infinite slope stability method**
- **Limit equilibrium method**
- **Finite element method (FEM)**

↓

Limitations

- **Simplified assumptions**
- **Scalability**
- **Flexibility**
- **Limited data availability**

Geological Approach

- Involves assumption that landslides occur in areas with specific geological characteristics
- Approach involves identifying those geological factors that control the occurrence of landslides, such as the type and structure of rocks, geological history, and soil properties **(Magliulo et al., 2008; Gorum et al., 2008; Pavel et al., 2010)**

↓

- **Geomorphological Mapping**
- **Soil Analysis**
- **Geophysical Survey**

↓

Limitations

- **Limited spatial coverage**
- **Limited data availability**
- **Lack of consideration of other factors e.g. weather, land use**

Statistical Approach

- Assume that the relationships between the landslide occurrence and the terrain attributes can be represented by mathematical functions **(Arabameri et al., 2019; Tahnh et al., 2019; Wubalem & Meten, 2020; Hemasinghe et al., 2018; Batar et al., 2021; Getachew & Meten, 2021)**

↓

- **Logistic regression (LR)**
- **Weight of evidence**
- **Multiple Regression**
- **Frequency ratio method**

↓

Limitations

- **Lack of Causality**
- **require large datasets**
- **Assumption of linearity**
- **Limited ability to incorporate expert knowledge**

Landslide Susceptibility Assessment Methods

Machine Learning Approach

- **Data-driven methods**: Various ML algorithms involve the development of a network of artificial neurons that can learn from the data to predict susceptibility **(Pourghasemi et al., 2013; Huang et al., 2018; Nefeslioglu et al., 2009; Park et al., 2018; Selamat et al., 2022; Saha et al., 2022)**

- **Support Vector Machines (SVM)**
- **Decision Trees**
- **Artificial Neural Networks (ANNs)**

Limitations

- **Dependence on quality and quantity of input data**
- **Less Interpretability if used as black boxes**
- **Limited data availability**

Hybrid Approach

- Uses multiple susceptibility assessment methods to take advantage of their strengths and overcome their weaknesses
- Developed by combining statistical methods with ML methods or geomorphic approach or expert opinions **(Shit et al., 2016; Leonardi et al., 2016; Jazouli et al., 2019)**

- **Weighted overlay analysis**
- **Fuzzy logic**
- **Analytic hierarchy process (AHP)**

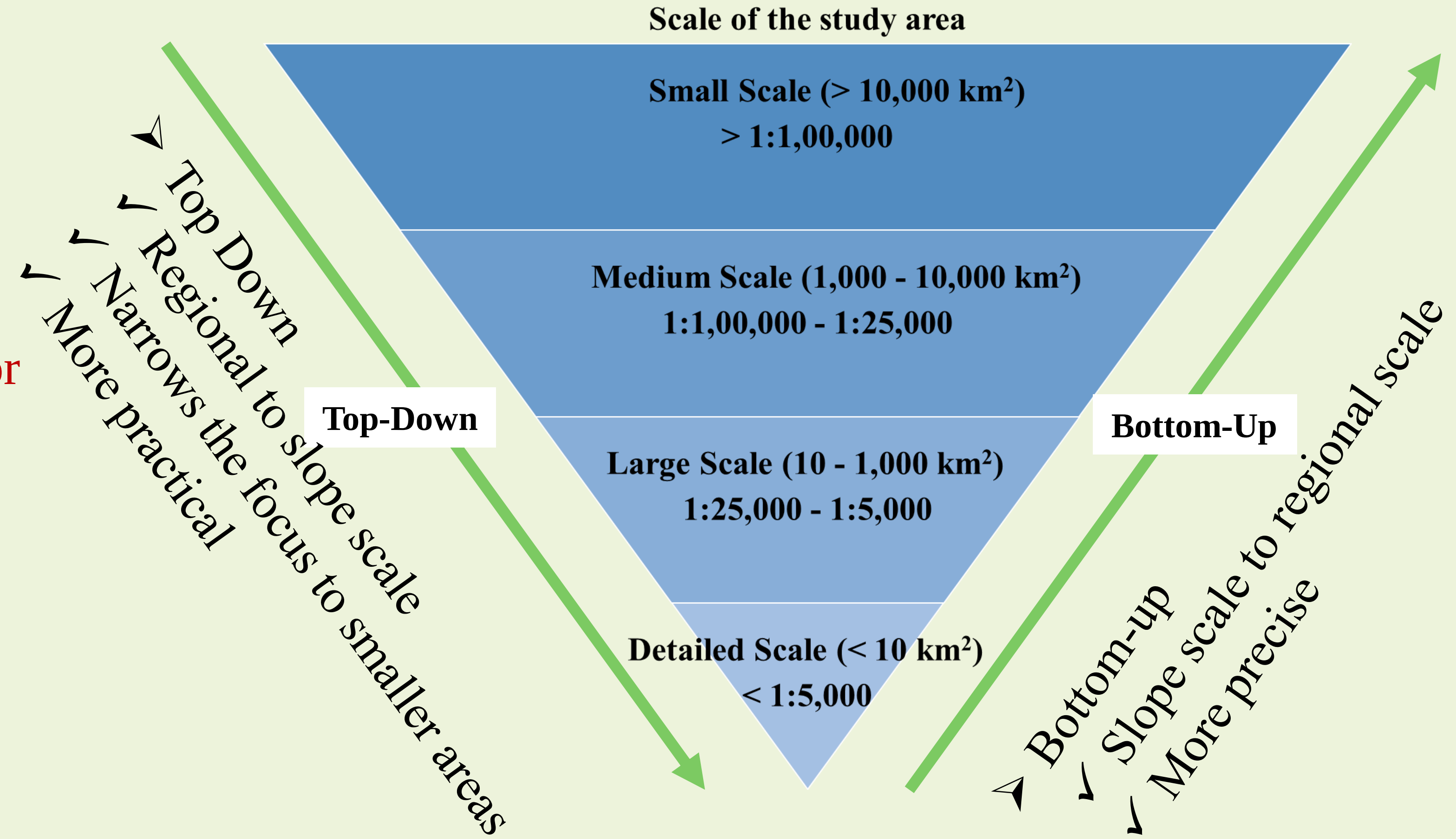
Limitations

- **Lack of Causality**
- **Require large datasets**
- **Assumption of linearity**
- **Limited ability to incorporate expert knowledge**

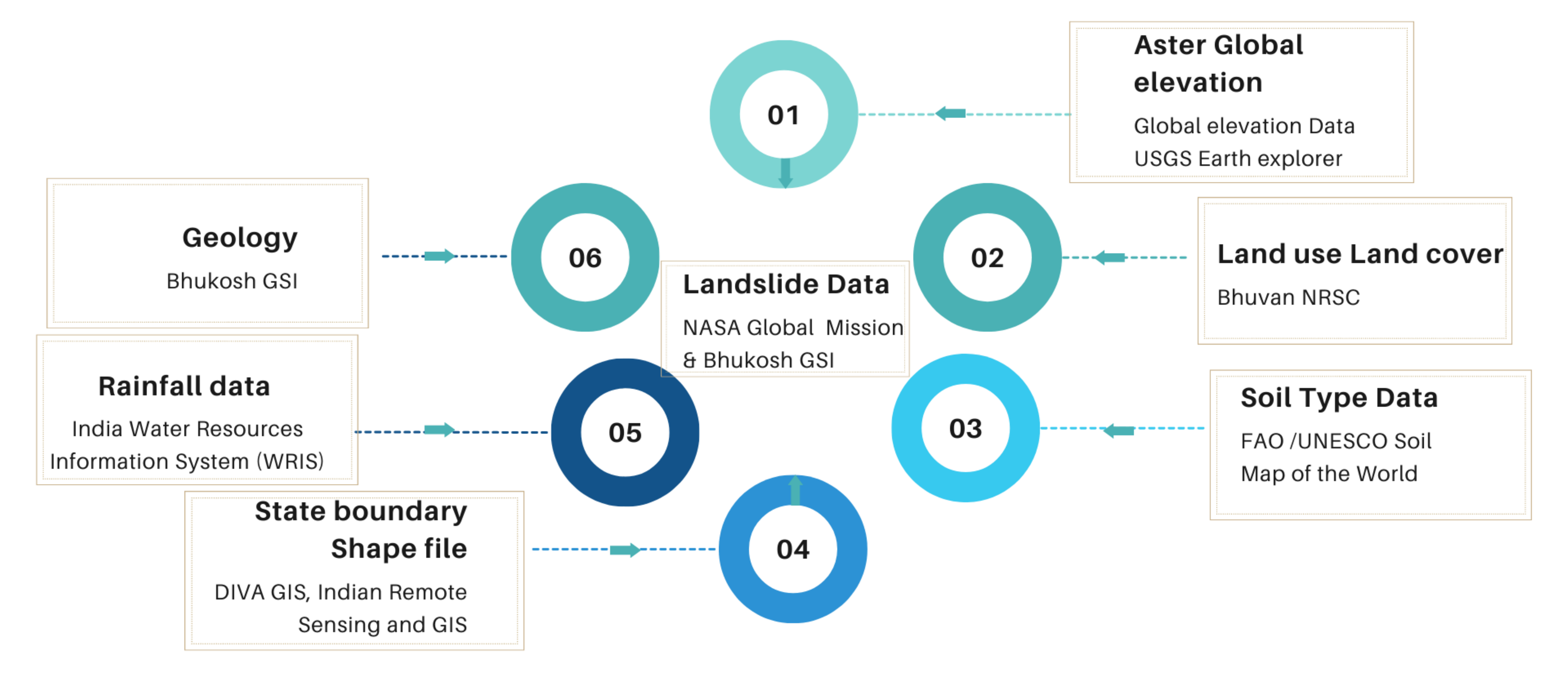
Choice of Landslide Susceptibility Assessment Methods

- **Which technique or approach to adopt?**
  - ❖ Investigation purpose
  - ❖ Extent of the area to be covered
  - ❖ **Scale of map to be produced**
  - ❖ Type of data to be used
  - ❖ Type of landslides
  - ❖ Availability of resources
  - ❖ Capability and skill set of evaluator
  - ❖ Accessibility of the study area

Multi-scale Approach For Landslide Susceptibility Analysis

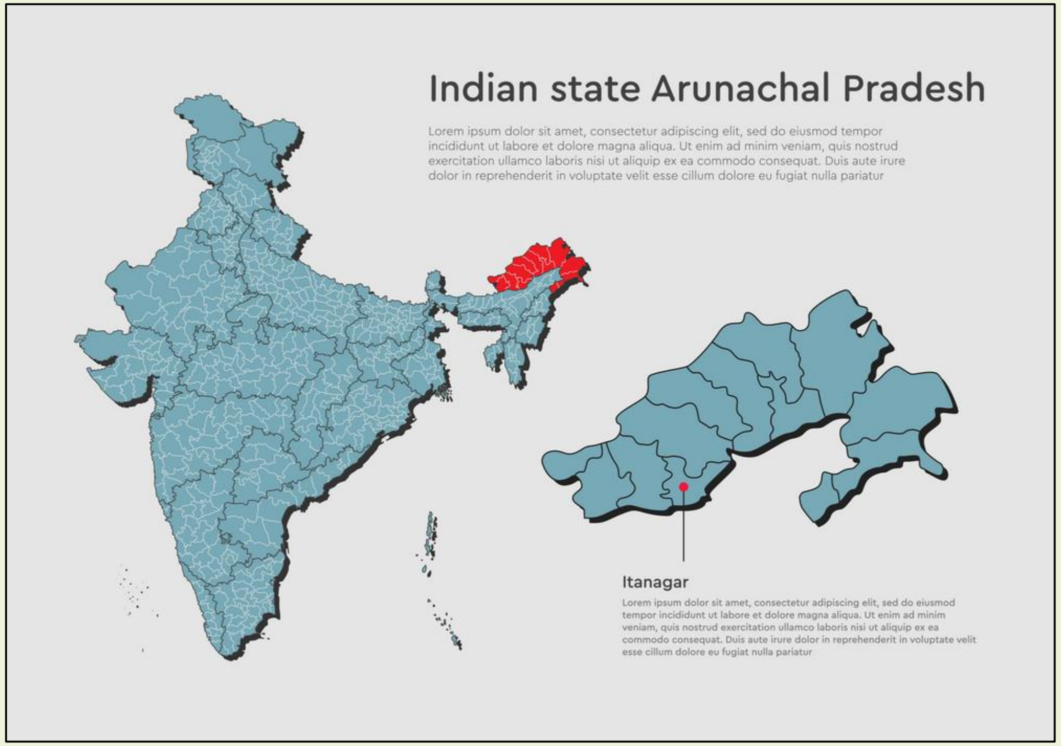


Basic Inputs to Landslide Susceptibility Assessment Methods

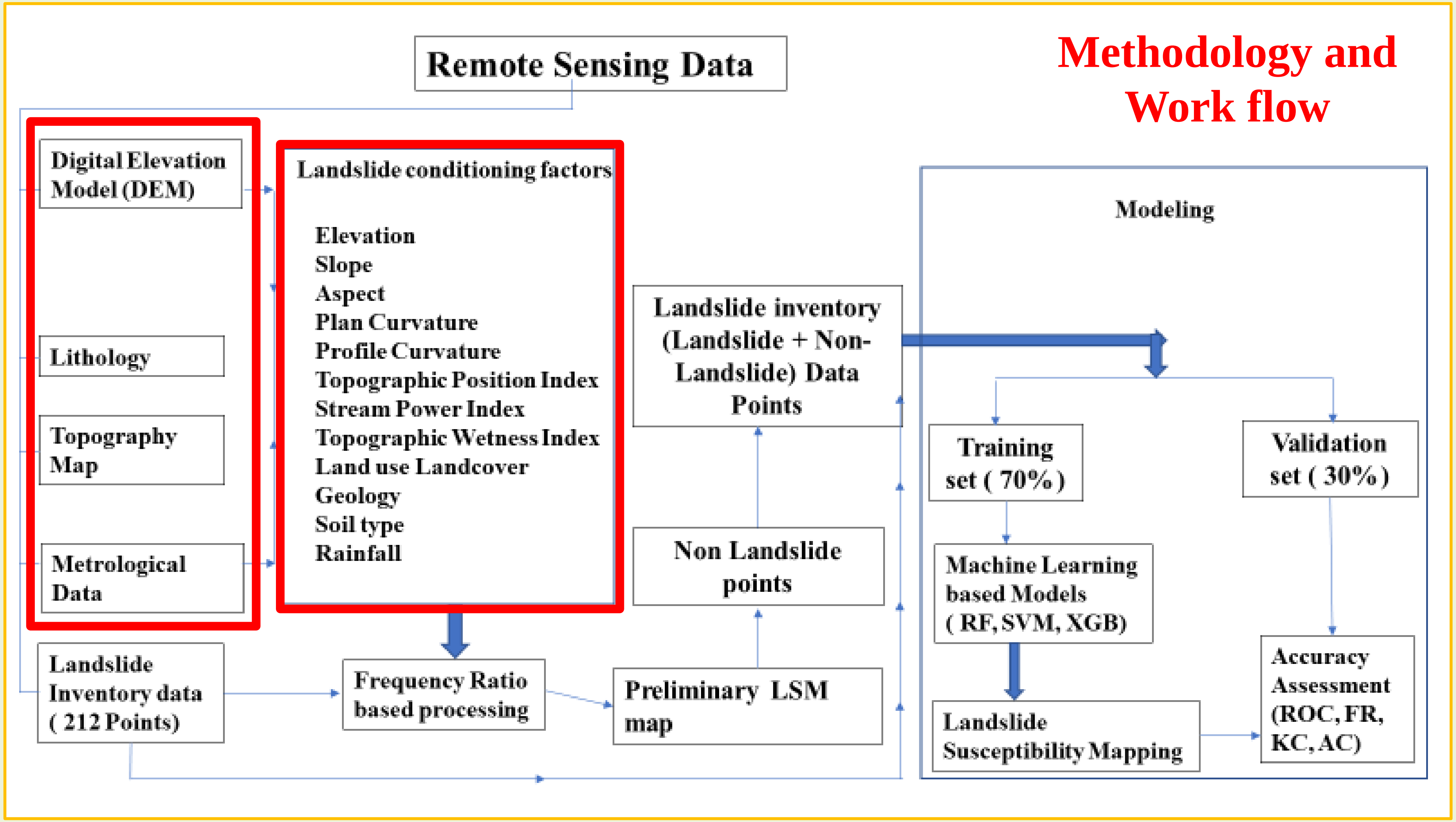


Study Area – Arunachal Pradesh

- **Arunachal Pradesh (Land of the rising sun)**
  - Foothills of eastern Himalayas
    - Area – 83,743 sq. km. (approx.)
  - Elevation range
    - Highest mountains – 7000 m above msl
    - Urban areas in plain lands – less than 100 m above msl
  - Slope gradient
    - 0º (plains) to 84.5º (vertical cliffs) – wide variability
  - Average annual rainfall
    - 3000 – 4000 mm
    - Max. rainfall – July; Min. rainfall – December
  - Topographic and Climatic condition
    - Region very conducive to landslides



Synergising Remote Sensing and ML to Landslide Susceptibility Assessment



Landslide Conditioning Factors

Digital Elevation Models (DEM)

- Critical component of LSM because they provide information about the topography of the terrain, which is an important factor in determining the likelihood of landslides **(Costanzo et al., 2012)**
- Provide **three-dimensional visualizations of terrain features**

Importance of DEM Resolution

High-Resolution DEMs

Captures more detailed information about the terrain, including small-scale features such as ridges, valleys, and channels.

Low-Resolution DEMs

May not capture small-scale features that could be important in identifying potential landslide locations. This can lead to a less accurate assessment of landslide susceptibility

Is high-resolution DEM is always the coveted one?

While high resolution DEM data can provide more detailed topographic information for landslide assessment, it is not always the best choice for every situation **(Chen et al., 2020)**

High Data volume: Result in large data volumes

High Cost: High resolution DEM data can be more expensive to acquire than lower resolution data, which can be a barrier for some researchers or organizations

Overfitting: High resolution DEM data can sometimes capture noise or unwanted local variations in topography

Resolution v/s Accuracy trade off: Increasing the resolution of DEM data may not necessarily result in more accurate landslide assessment results

Other factors, such as the **Quality of the data acquisition and processing**, the availability of ground truth data, and the modeling techniques used, also plays a significant role in determining the accuracy of landslide assessment

DEM and Rainfall-Induced Landslide

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Influence of digital elevation models on the simulation of rainfall-induced landslides in the hillslopes of Guwahati, India

Check for updates

Chiranjib Prasad Sarma[a], Arindam Dey[a,*], A. Murali Krishna[b]

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A R T I C L E I N F O

Keywords:
Digital elevation models
Rainfall-induced landslides
TRIGRS
Receiver Operating Characteristics
LR_{class}
Rainfall events

A B S T R A C T

Topographic input parameters such as slope, curvature, and drainage area are derived from a Digital Elevation Model (DEM) representing the spatial elevation, and are widely used as important sources of geospatial information. Based on the chosen DEM and its derived paramters, physically based GIS models, such as TRIGRS, can compute the transient degradation of the hillslope stability due to rainfall infiltration to identify the landslide occurrences in the considered region. Hence, it is inadvertent that the accuracy of the DEM will significantly affect the outcome of the TRIGRS simulations. Obtaining a high-resolution DEM (using LiDAR, dGPS or other such ground based advanced surveying methods) for a large area is an expensive affair and unavailable in

Sarma, C. P., **Dey, A.** and Murali Krishna, A. (2020) "Influence of digital elevation models on the simulation of rainfall-induced landslides in the hillslopes of Guwahati, India" ***Engineering Geology (Elsevier)***, Vol. 268, Article No. 105523, pp. 1-13. (DOI: https://doi.org/10.1016/j.enggeo.2020.105523)

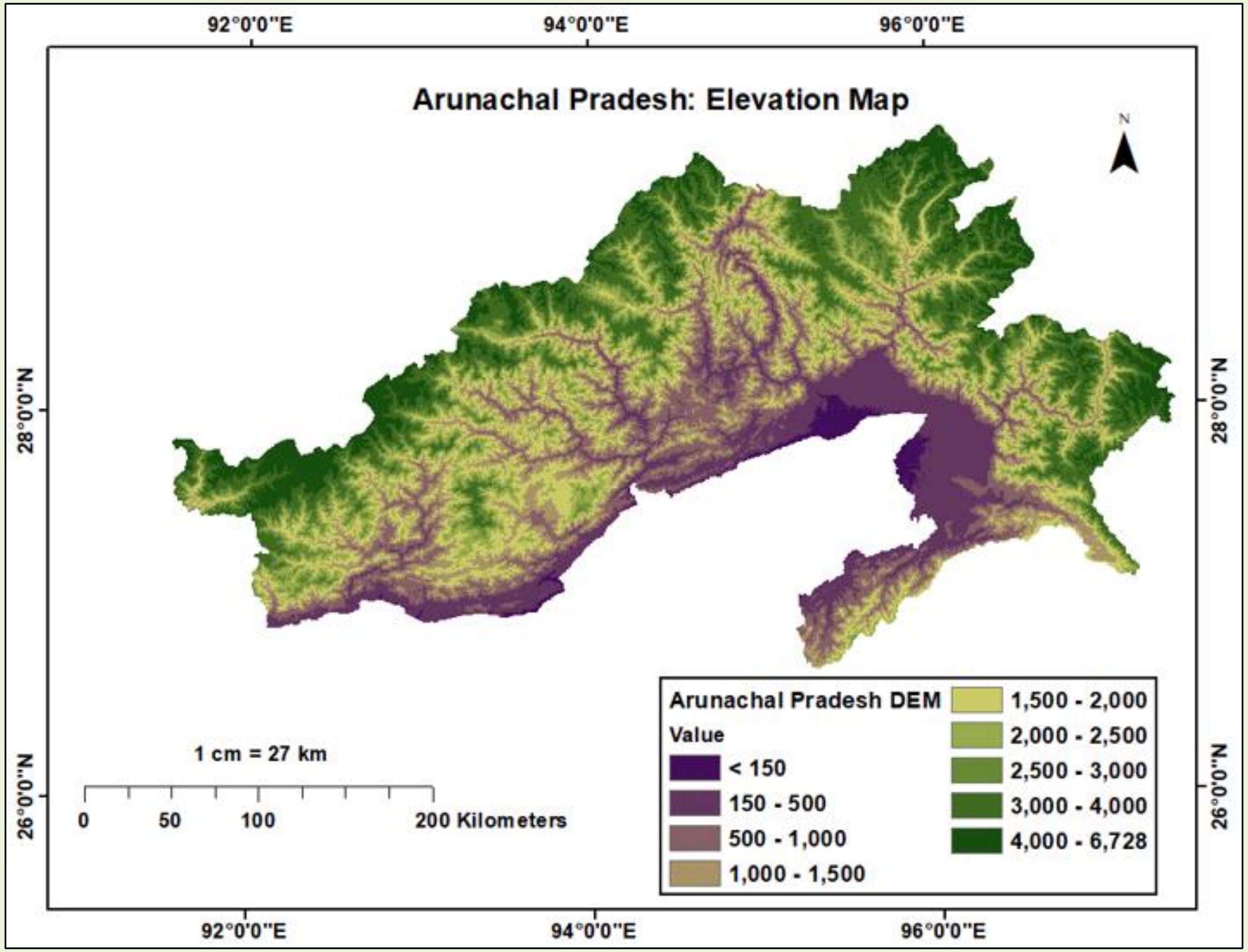
Landslide Conditioning Factors

Applicability of 30 m DEM for Landslide assessment

DEMs with resolutions of 30 m have been widely used for landslide assessment due to their availability and reasonably high accuracy

Several researchers have shown that the 30 m DEM was able to accurately identify the landslide-prone are

- **Ranjan et al., 2018: Uttarakhand**
- **Pal et al., 2019: North Sikkim**
- **Singh et al., 2017: Himachal Pradesh**
- **Das et al., 2019: Darjeeling Himalaya**
- **Chang et al., 2019: Taiwan**.

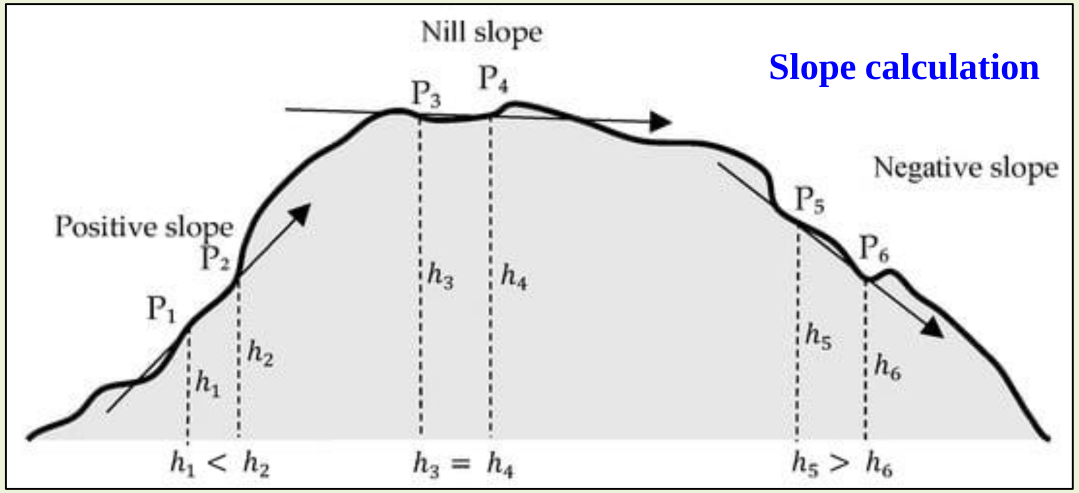


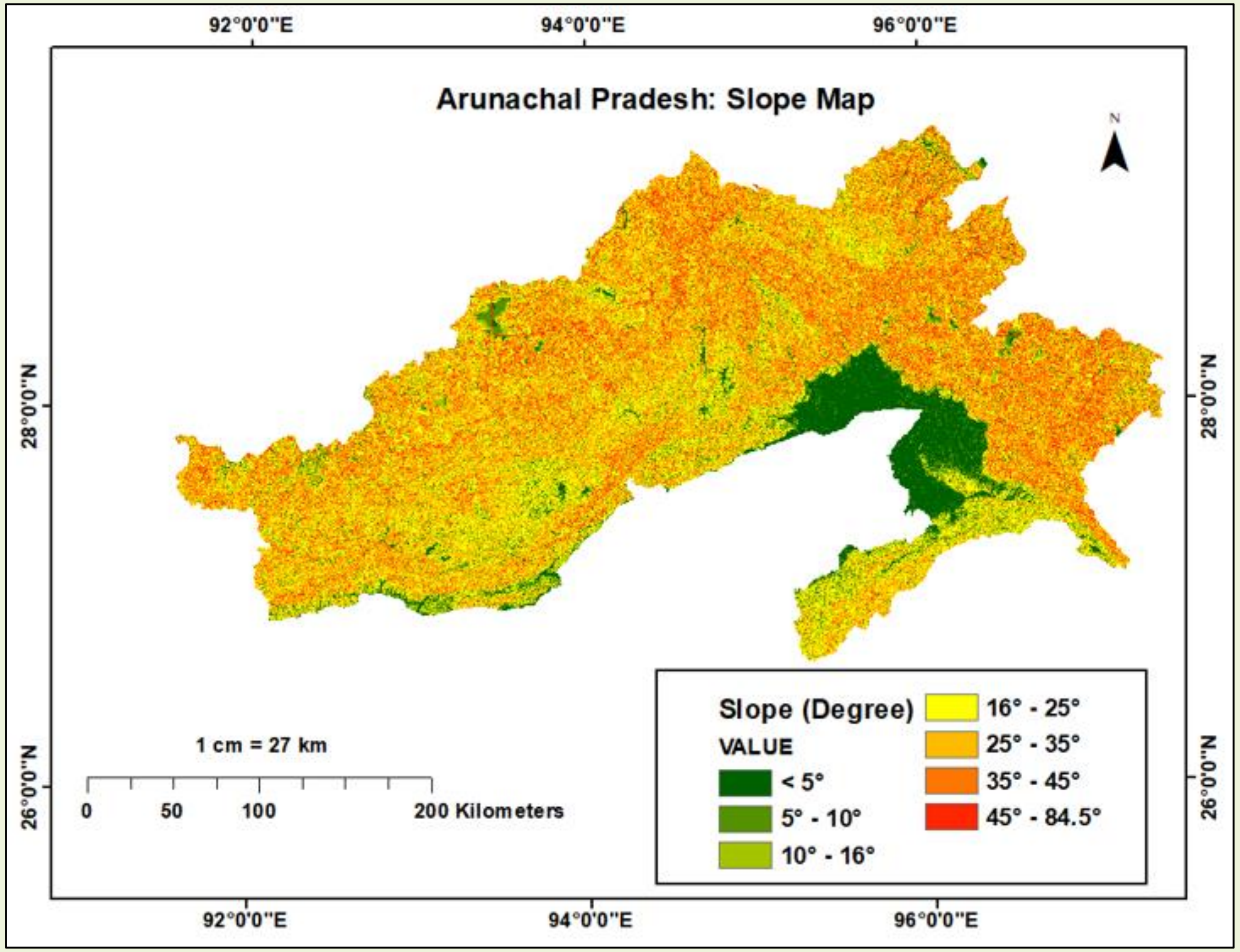
Digital Elevation map of Arunachal Pradesh

Landslide Conditioning Factors

Slope

- Slope is considered as the first derivative of the elevation; this is calculated to **quantify variation in elevation over a distance**
- Steep slopes are more prone to landslides than gentle slopes: Influence of gravitational drag
- Long and narrow slopes are more susceptible to landslides than short and wide slopes
- Steep slopes also tend to have a thinner soil cover, which reduces the stability of the slope. In contrast, gentle slopes have a thicker soil cover, which provides better support and stability to the slope





Slope map of Arunachal Pradesh

Landslide Conditioning Factors

Aspect

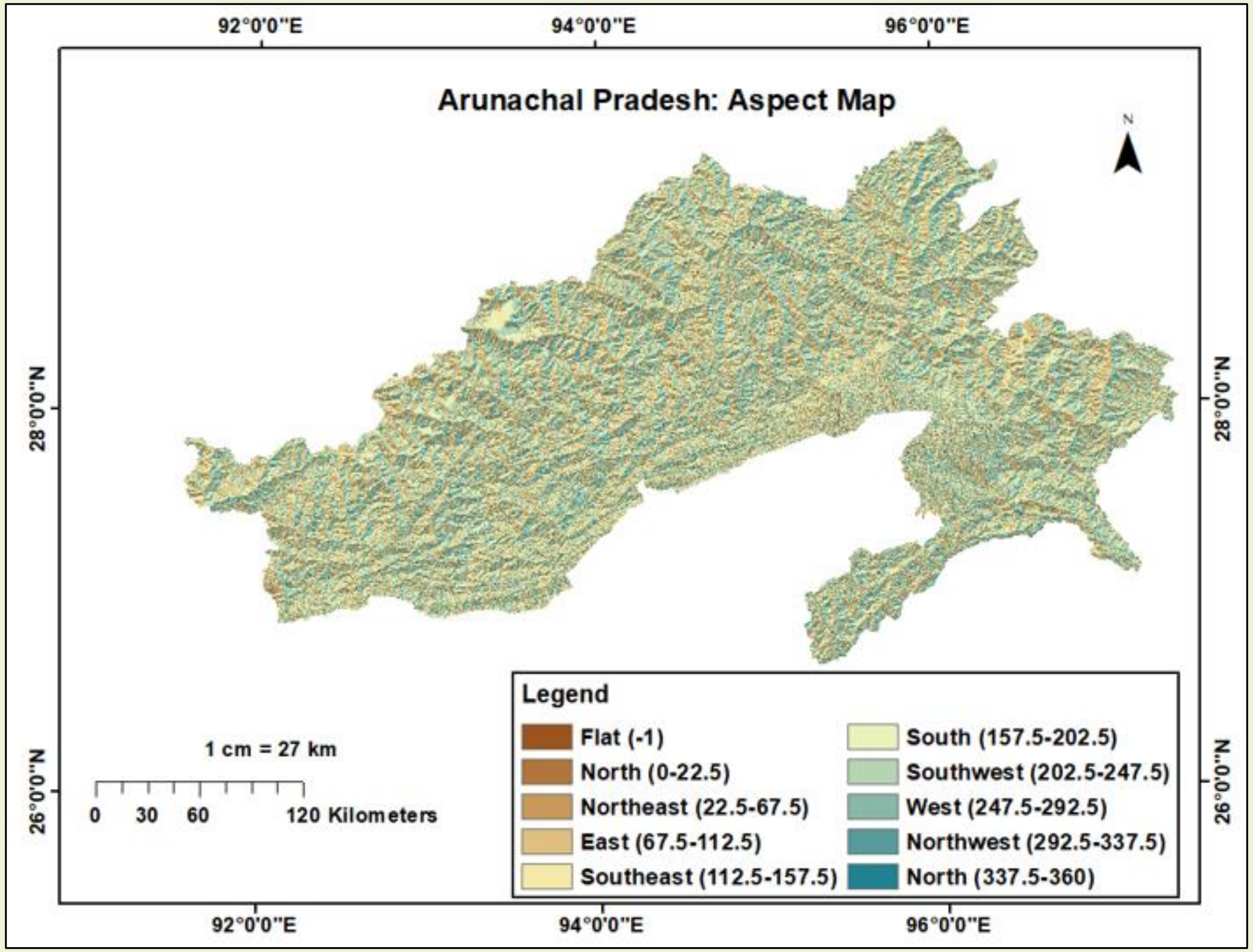
- Refers to the **orientation or direction that a slope is facing, measured in degrees clockwise starting from the north**

- Affects the amount of solar radiation and moisture that a slope receives, which in turn affects
  : distribution of vegetation
  : Amount of soil moisture
  : Rate of soil erosion

- Influences the distribution of geological features such as fractures, faults, and joints

- Influences the amount of snow accumulation on a slope, which can affect the slope's stability and susceptibility

- Slopes that face north in the northern hemisphere tend to have greater snow accumulation than those that face south, and heavy snow loads can increase the weight and water content of the soil **(Maren et al., 2005)**



Aspect map of Arunachal Pradesh

Landslide Conditioning Factors

Curvature: Concavity of Convexity of a slope

Plan curvature

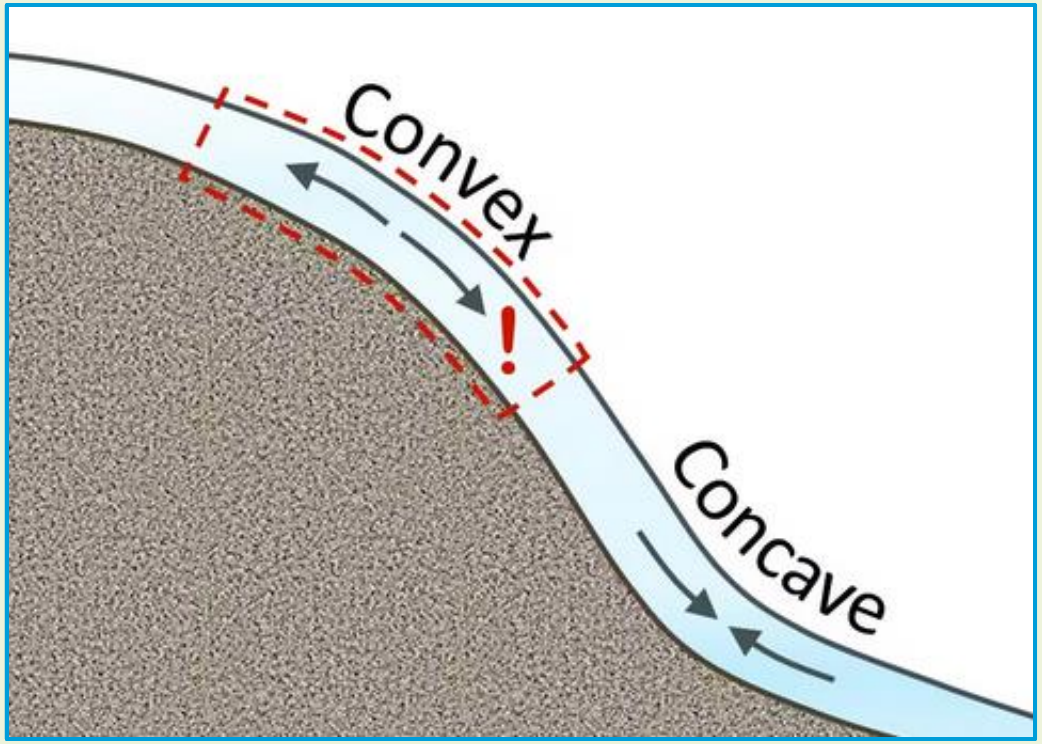
- Refers to the **curvature of a slope in a horizontal plane, and it is measured along a contour line**.
  - A convex slope has a positive plan curvature, while a concave slope has a negative plan curvature **(Nasiri Aghdam et al., 2016)**
  - Slopes with negative plan curvature tend to collect water, which can decrease the shear strength of the soil or rock, making the slope more susceptible to landslides

Profile curvature

- **Measured perpendicular to a contour line**
- Measures the acceleration/deceleration of the flow

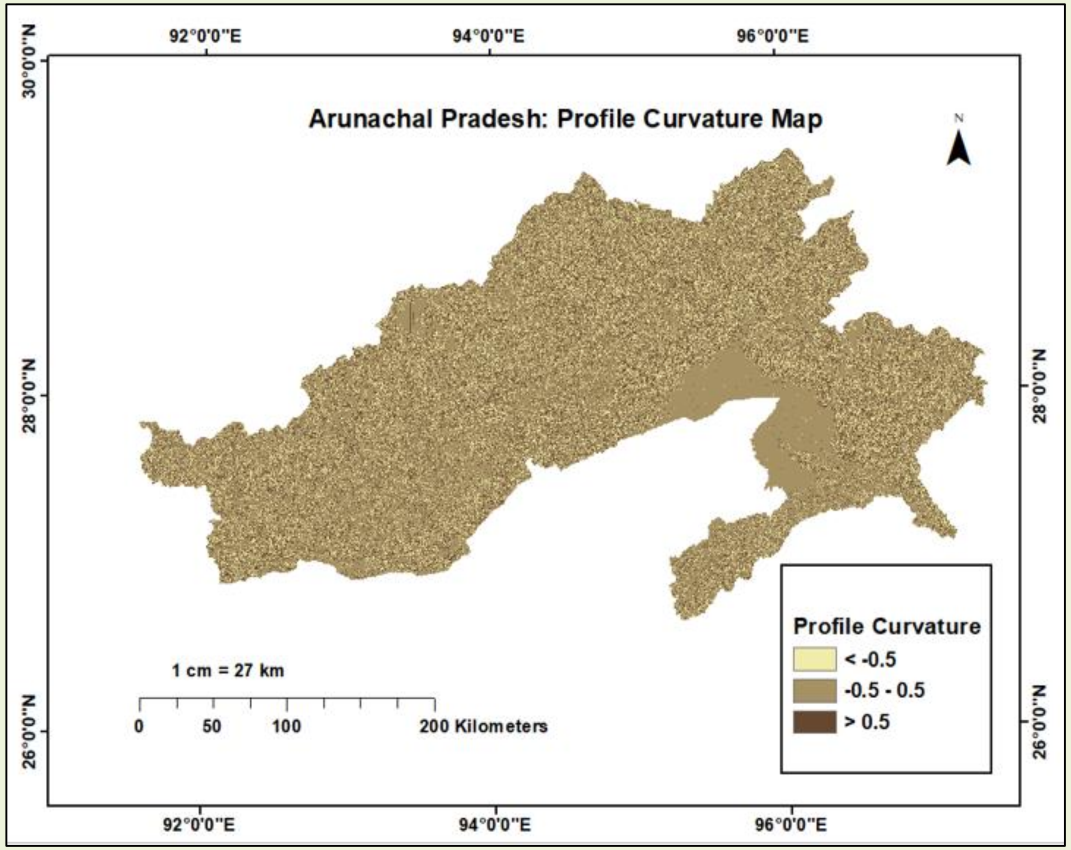
The presence of negative curvature (i.e. concave slope in either plan or profile can increase the risk of landslides

The convex shape promotes the rapid flow of water across the slope, reducing the accumulation of water on the surface thus reducing the risk of failure.

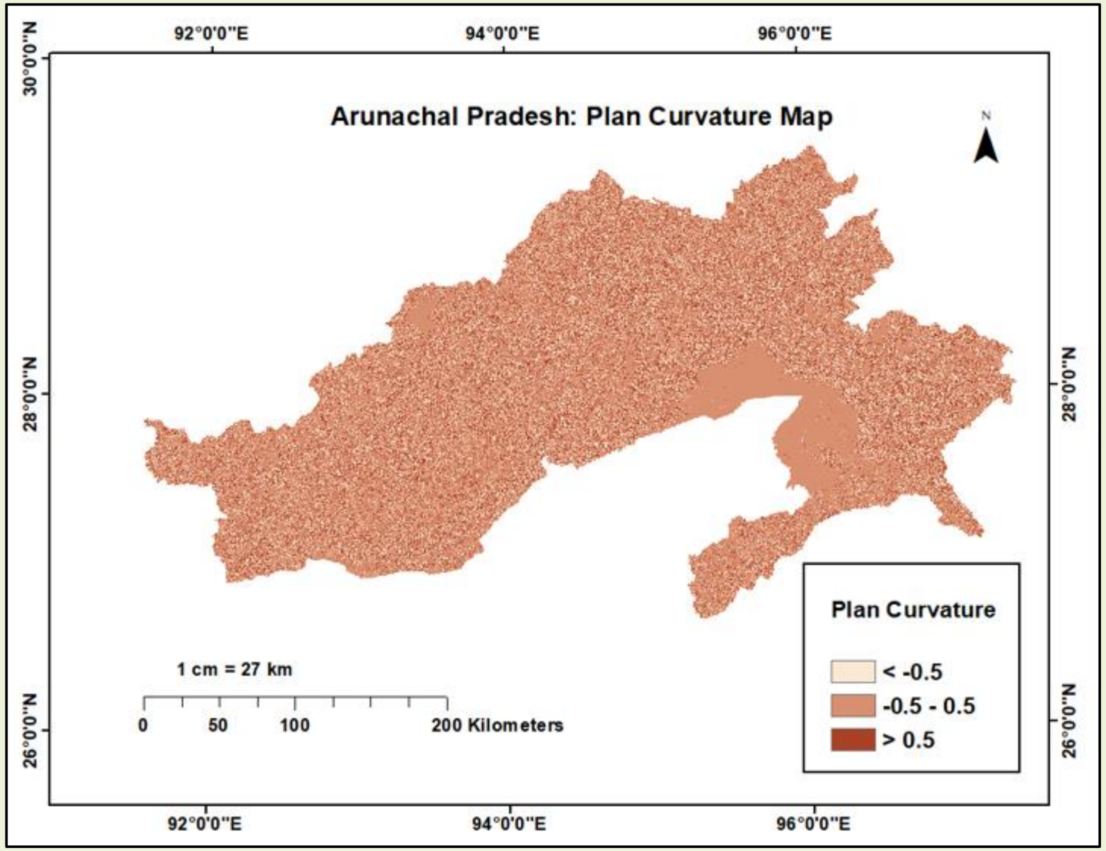


Curvature of a slope

Landslide Conditioning Factors



Profile curvature map of Arunachal Pradesh



Plan curvature map of Arunachal Pradesh

Landslide Conditioning Factors

Topographic Position Index (TPI)

Mostly the researchers have carried out **landform classification** using survey methods and manual delineation

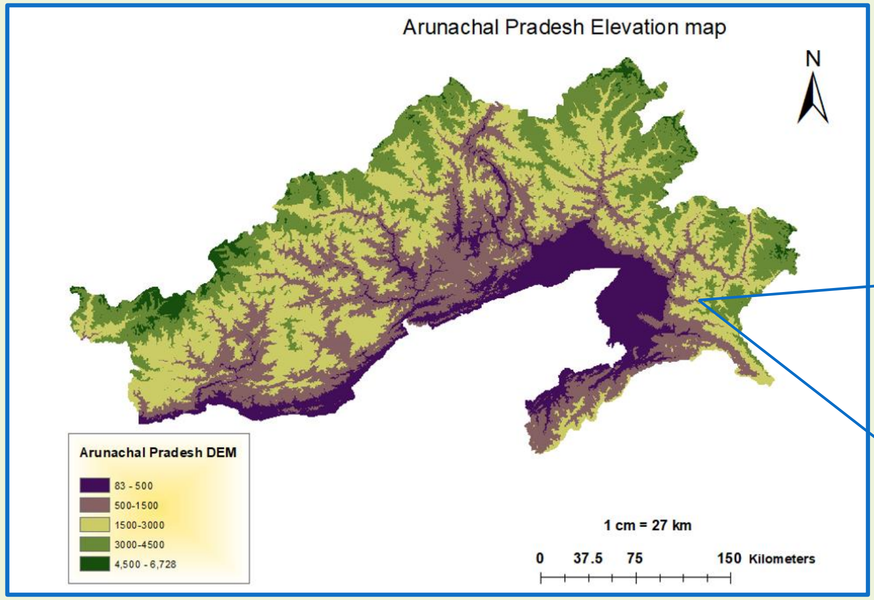
Integrating remote sensing data and GIS technique can automate identifying the landform using topographic position Index data as one of emote sensing data

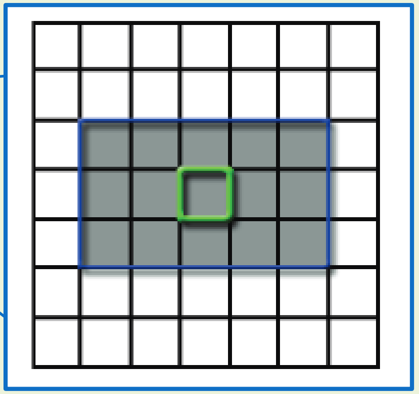
- Since the only input required is a DEM, TPI can be readily generated almost anywhere.

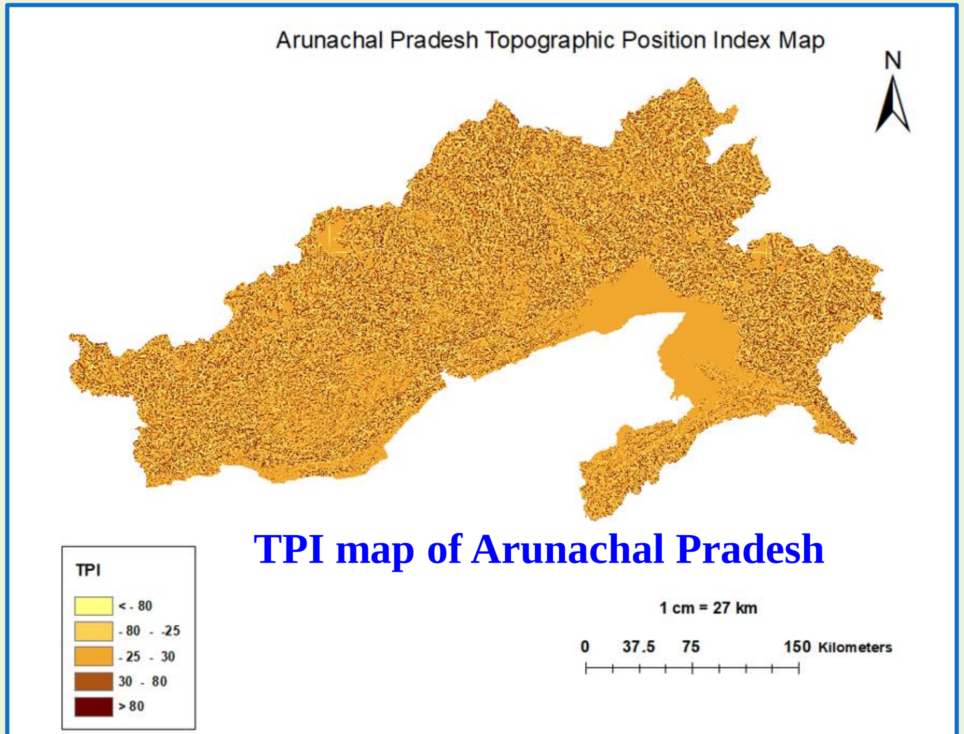
TPI compares the **elevation of each cell in a DEM to the mean elevation of a specified neighbourhood around that cell**

The mean elevation is subtracted from the elevation value at the centre

- Area near the peak of the hill (+ve value).
- Areas at the foot of the hill, (-ve value).
- TPI values near zero or close to zero are either flat areas or areas of constant slope





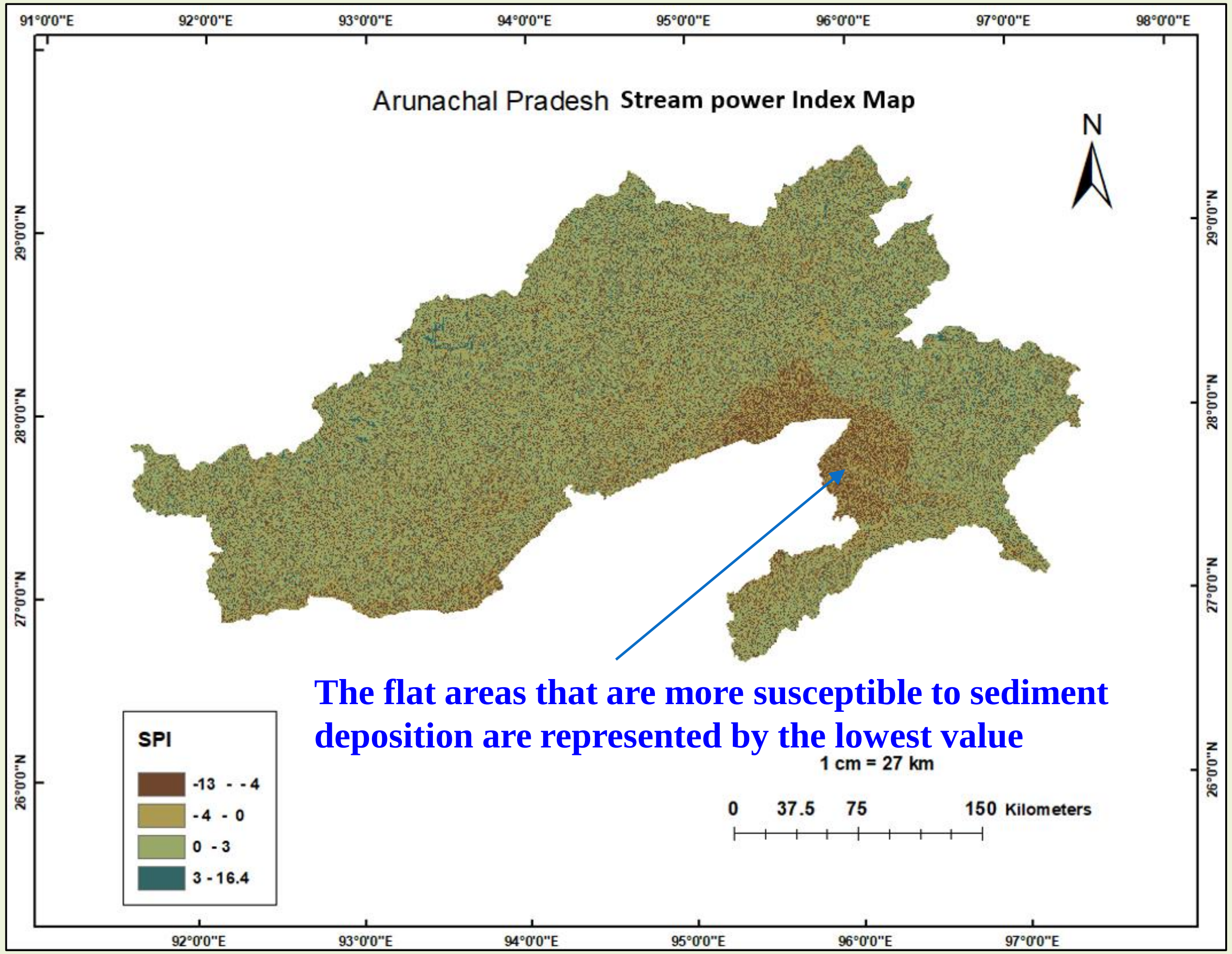


TPI map of Arunachal Pradesh

Landslide Conditioning Factors

Stream Power Index (SPI)

- Identifies **areas of occurrence of channel erosion, which can lead to changes in the landscape** and potentially contribute to landslides **(Vijith and Wan, 2019)**
- Monitors changes in river morphology over time, which can indicate changes in the temporal potential for landslides
- If the SPI is high, erosive power of a stream is high, rendering the slopes adjacent to the stream more prone to landslides **(Arabameri et al. 2018)**
- A decrease in SPI may indicate that sediment is accumulating in a river channel, which can increase the potential for landslides due to reduction of the stability of the surrounding slopes
- SPI < -4 indicates the area highly likely to deposition, while SPI > 3 shows the area likely to be affected by erosion
- SPI of the Arunachal Pradesh study area varies from **-13 to 16.4** indicating the differential erosive power of the streams in the region

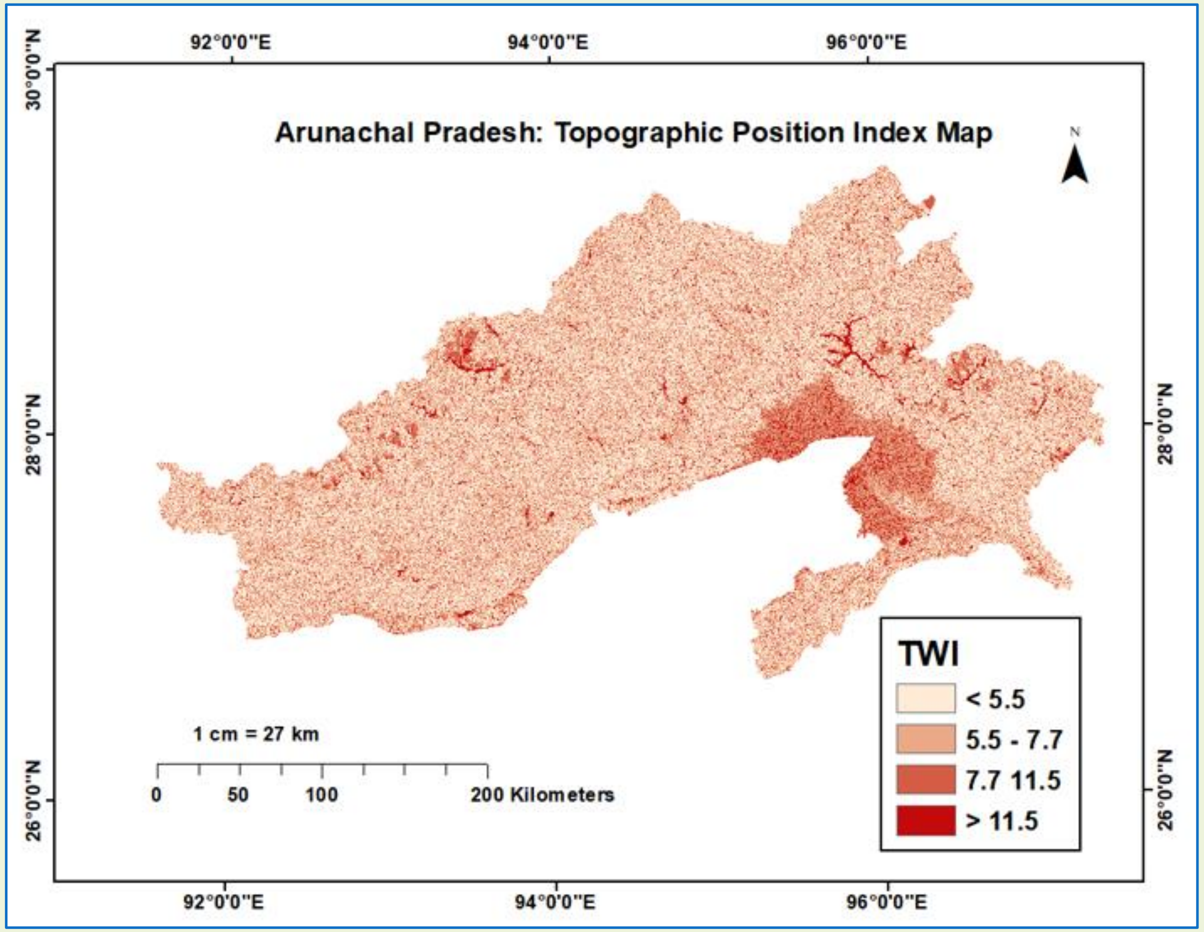


SPI map of Arunachal Pradesh

Landslide Conditioning Factors

Topographic Wetness Index (TWI)

- Measure of **the relative water saturation of the landscape based on local upslope contributing area and slope angle**
  - Primarily used to describe soil moisture conditions
- An indicator that measures the potential of water accumulation in a specific region
  - A high index value indicates a high potential of water accumulated due to a low slope and vice versa **(Rozycka et al., 2017)**
- TWI is commonly used in soil and vegetation studies, wetland delineation
- Important for landslide susceptibility mapping as higher moisture accumulation tends to reduce the strength or resistance of the soil from gravitational drag

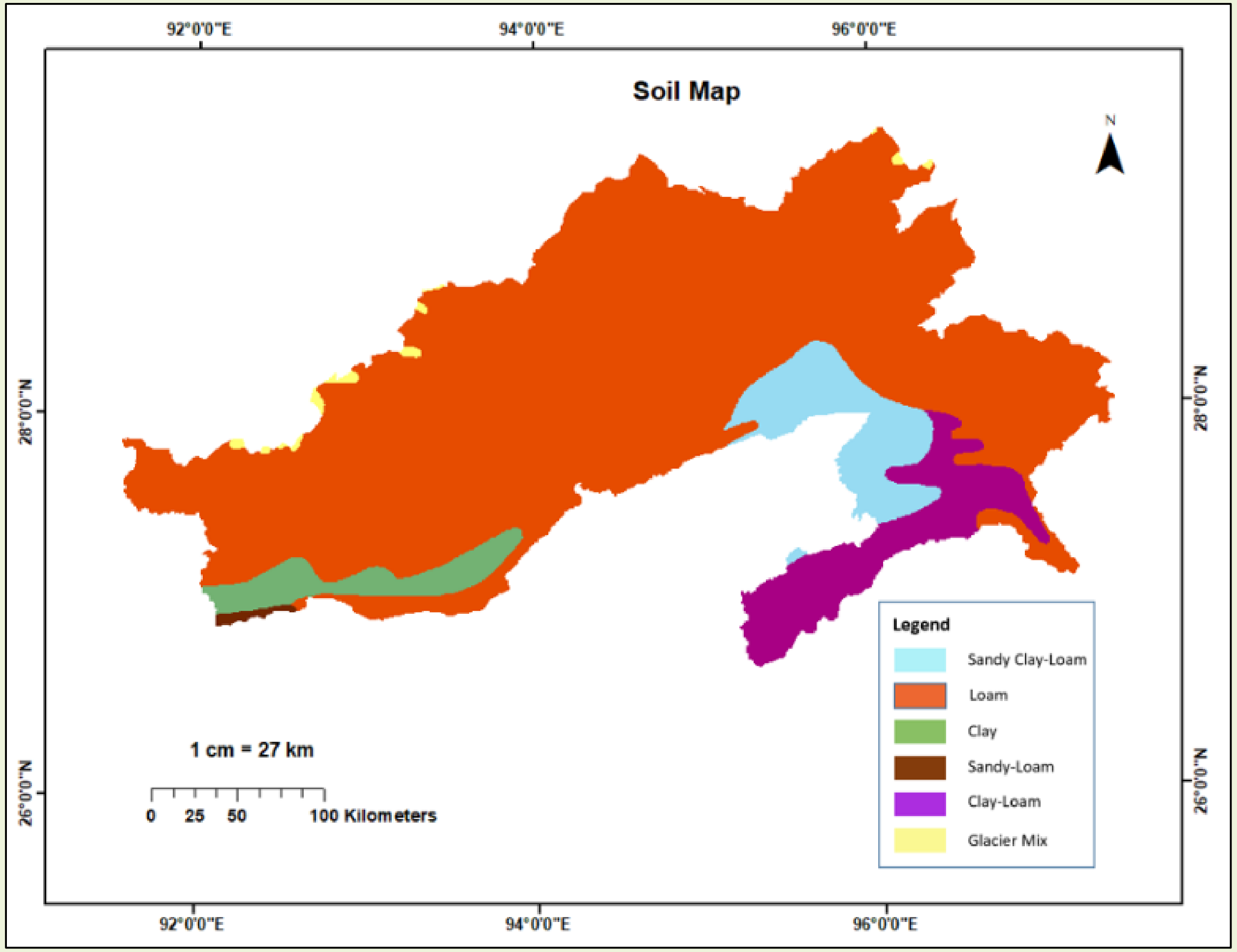


TWI map of Arunachal Pradesh

Landslide Conditioning Factors

Soil Typology

- Crucial element in assessing the probability and intensity of landslides
- **Geological factors such as the rock type, orientation, and structure** can all influence the susceptibility of a slope to landslides
- Different soil types have varying physical and mechanical properties, such as porosity, permeability, shear strength, and cohesion, this affects the stability of slopes **(Das, 2011; Mezughi et al., 2011)**
- Loamy soil (sandy-silty-clay) tend to be more susceptible to landslides because they have reasonably low permeability to hold water, thereby increasing the unit weight of the system and reducing shear strength of the soil, while relatively lesser cohesion to provide resistance to soil drag



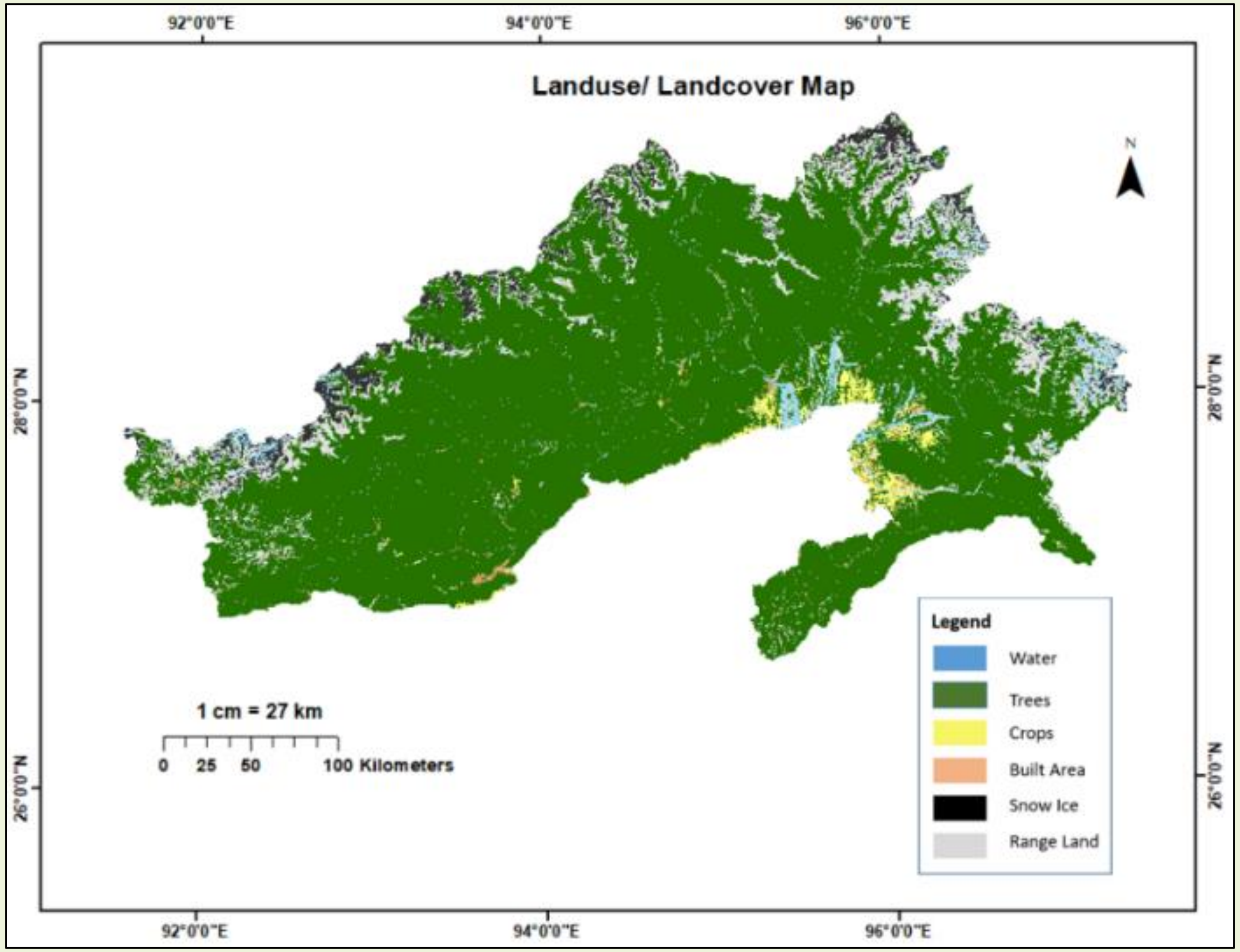
Soil map of Arunachal Pradesh

Landslide Conditioning Factors

Land use and Land cover

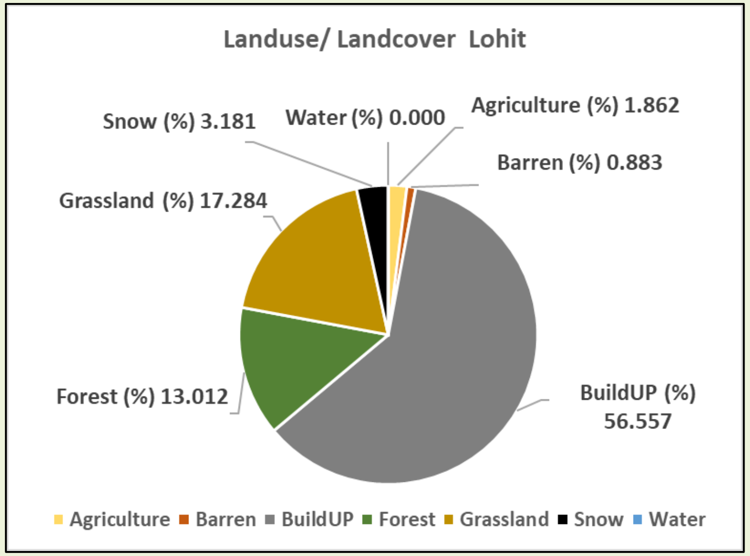
How land use and land cover can impact landslides?

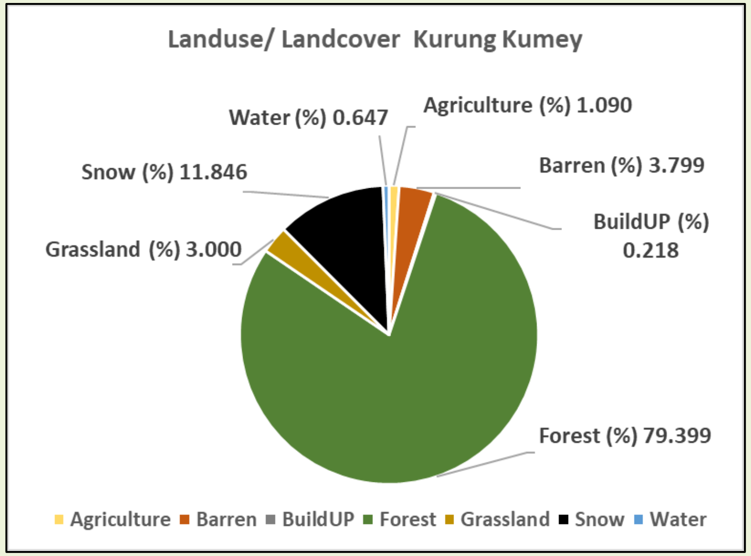
- **Vegetation cover**
  - Binds the soil together and reduce the chances of soil erosion
- **Land use activities**
  - Land use activities such as mining, quarrying, and construction can alter the natural landscape, making it more vulnerable to landslides
- **Urbanization**
  - Altering the natural drainage patterns of an area, increasing the amount of impervious surfaces, and changing the slope angle of the land

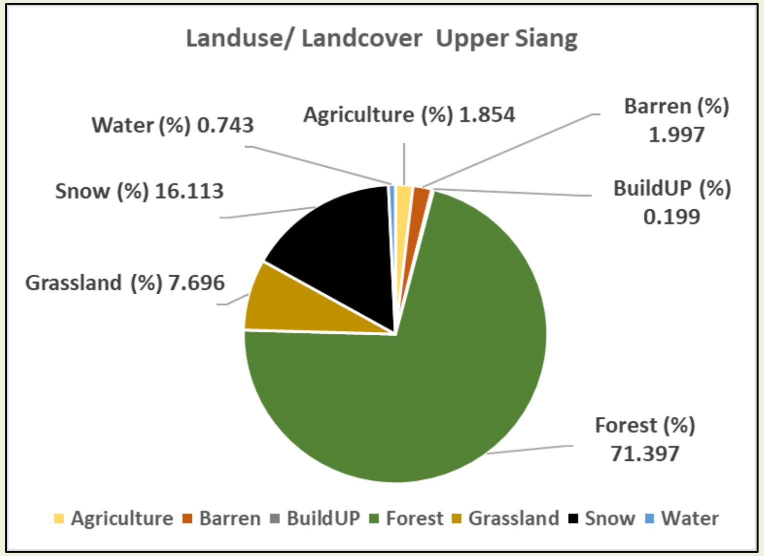


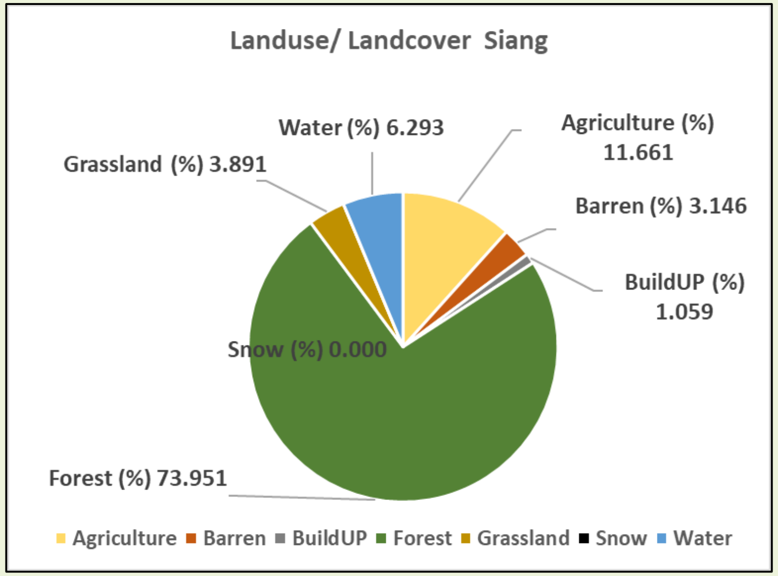
LULC map of Arunachal Pradesh

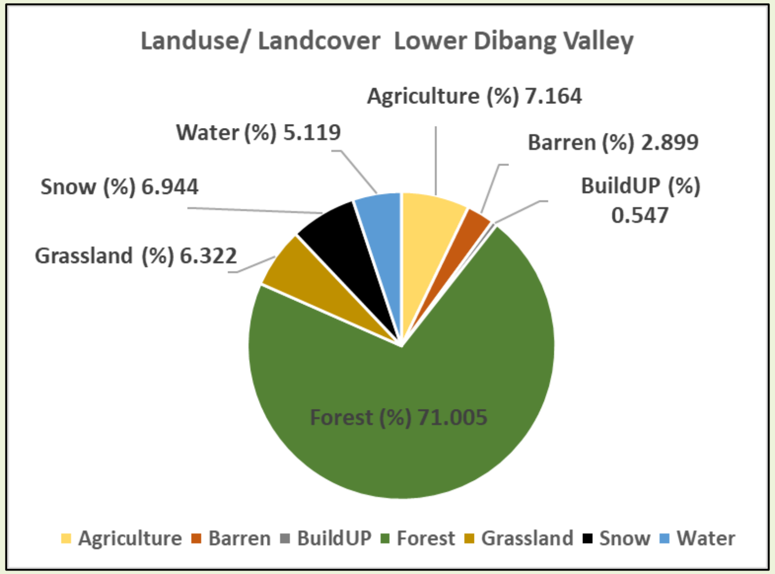
District-wise LULC of Arunachal Pradesh

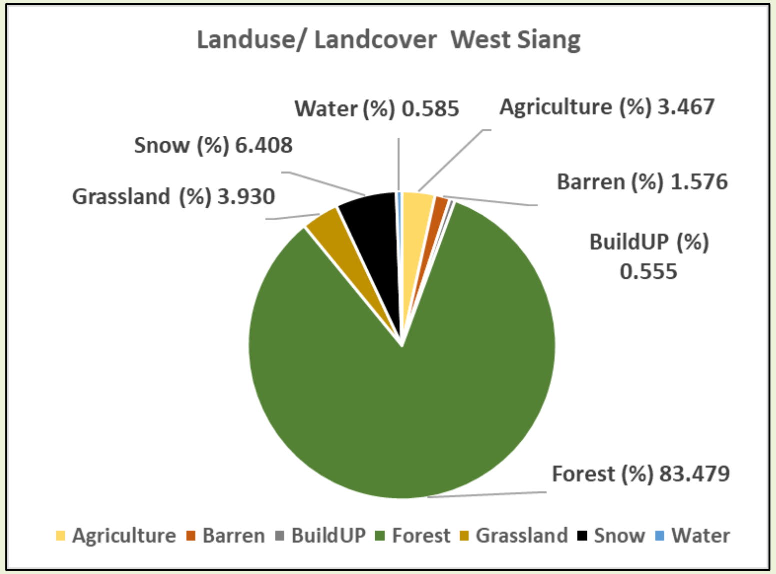




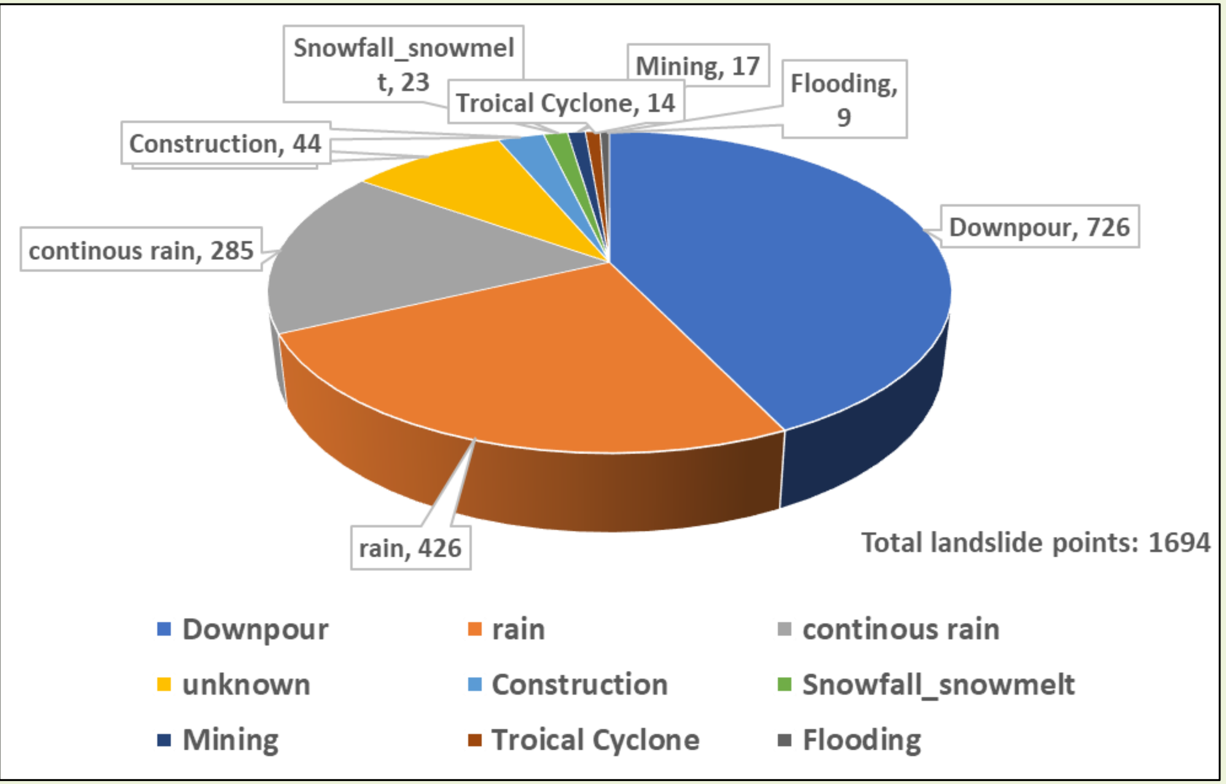




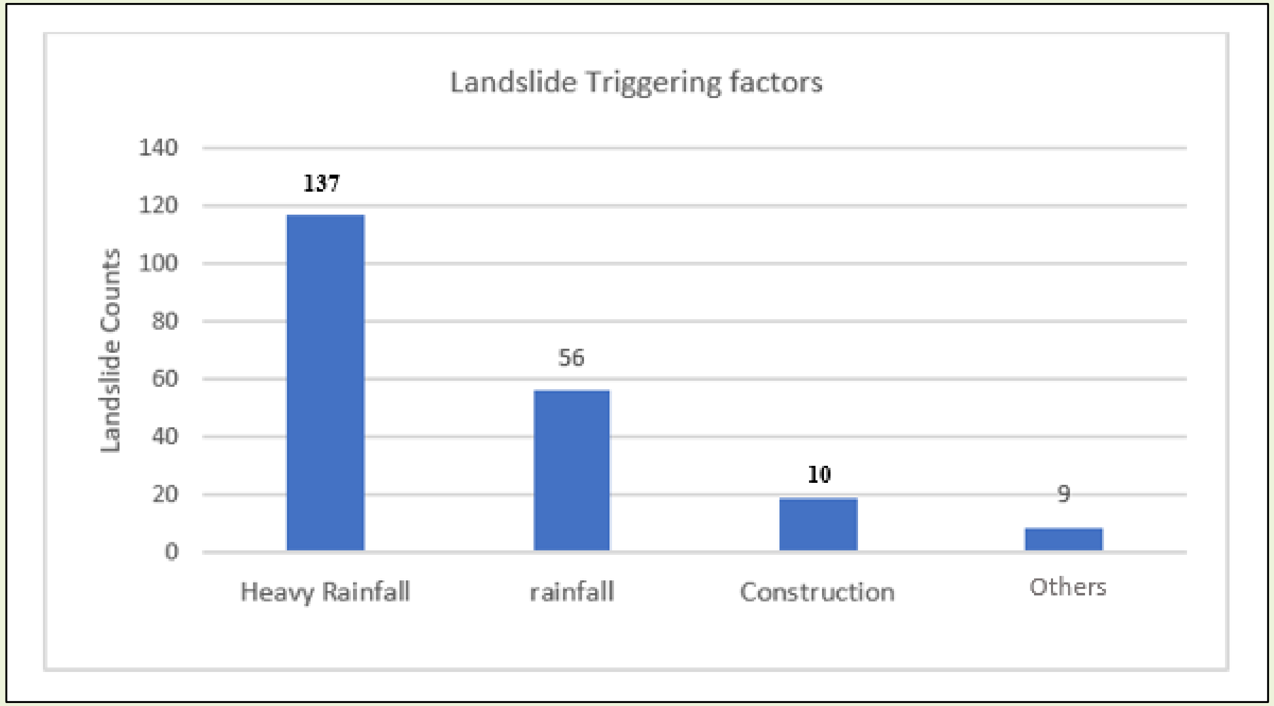




Rainfall as Major Causative and Triggering Factor for Landslide



Triggering factors recorded for landslide in India



Triggering factors recorded for landslide in Arunachal Pradesh

Landslide Conditioning Factors

Rainfall

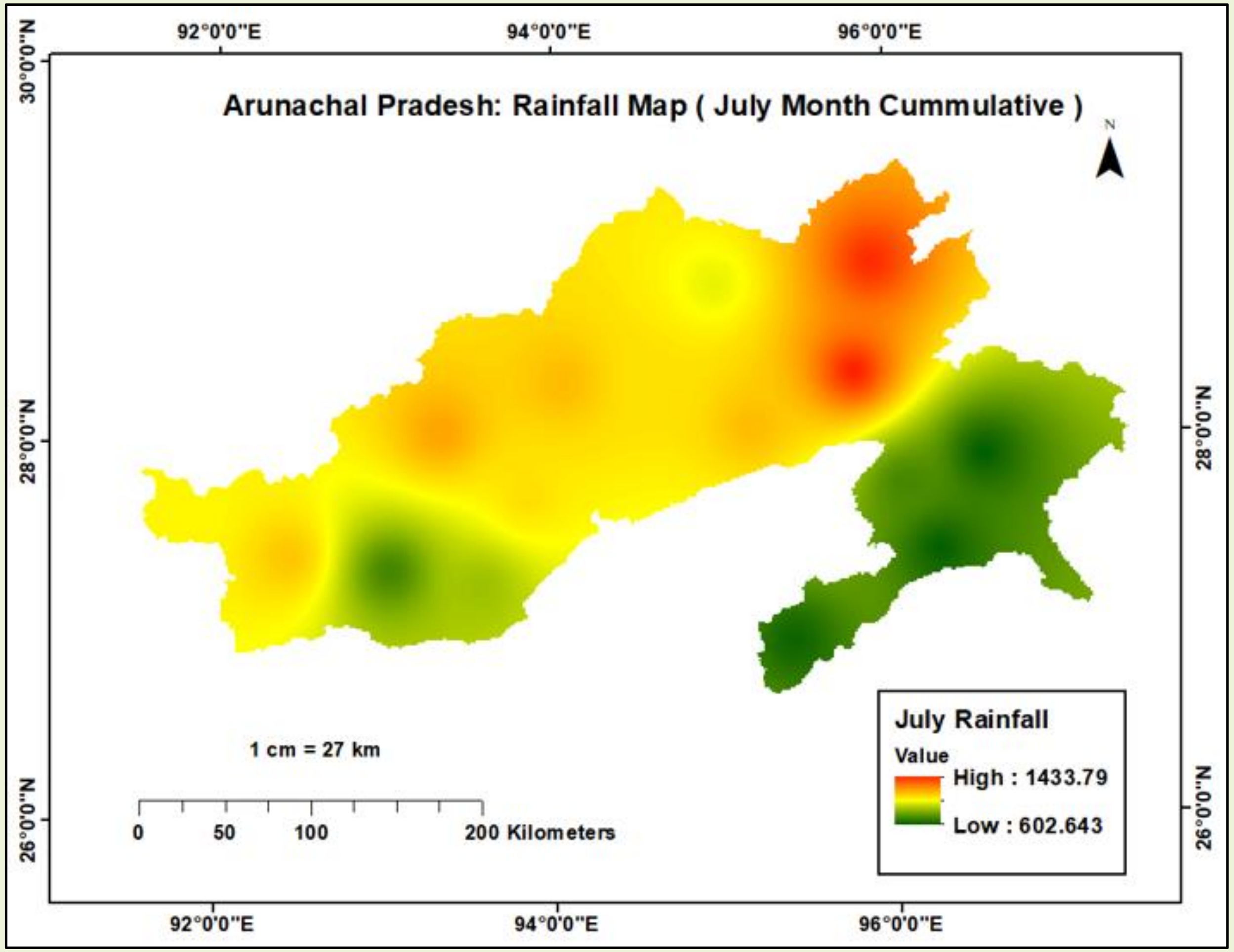
Rainfall is a primary element that influences the susceptibility and occurrence of landslides.

It provides moisture that can reduce the shear strength of soil or rock masses, leading to the initiation and propagation of landslides.

Rainfall tends to accumulate in certain areas, leading to localized saturation and increased susceptibility to landslides **(Tseng et al., 2017)**

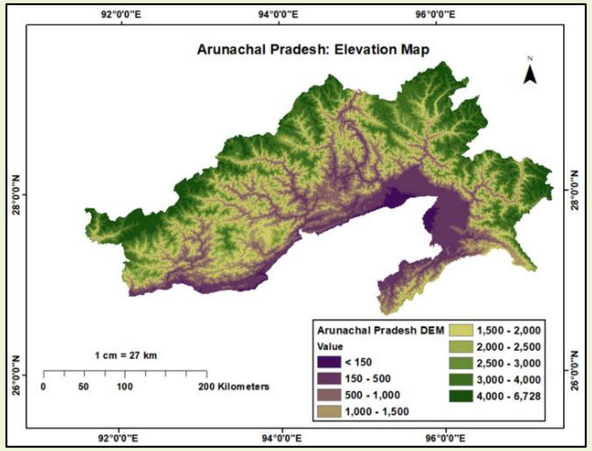
Features of rainfall influencing landslide occurrence

- **Rainfall Duration**
- **Rainfall Intensity**
- **Rainfall Spatial Distribution**

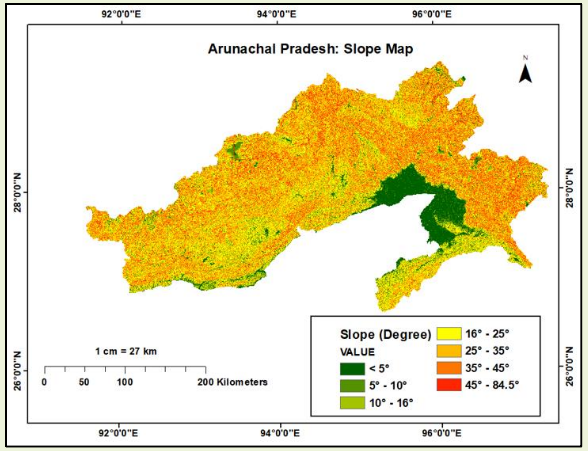


Rainfall map of Arunachal Pradesh

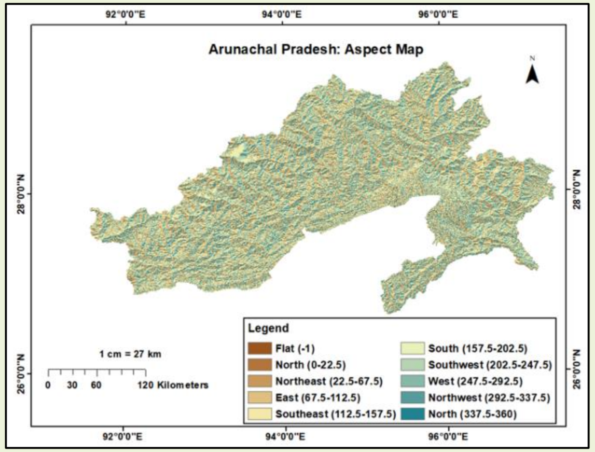
Collation of all Landslide Conditioning Factors



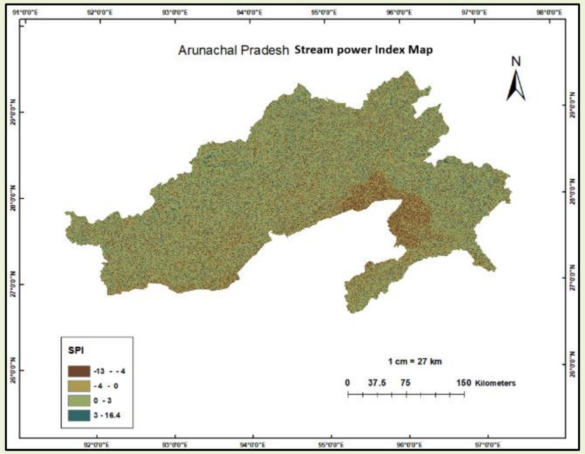
Elevation



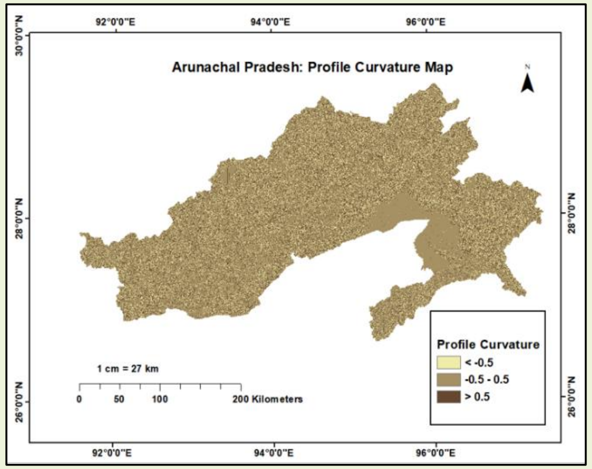
Slope



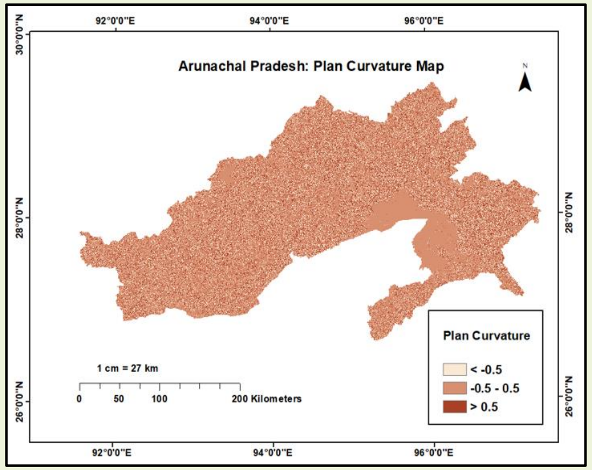
Aspect



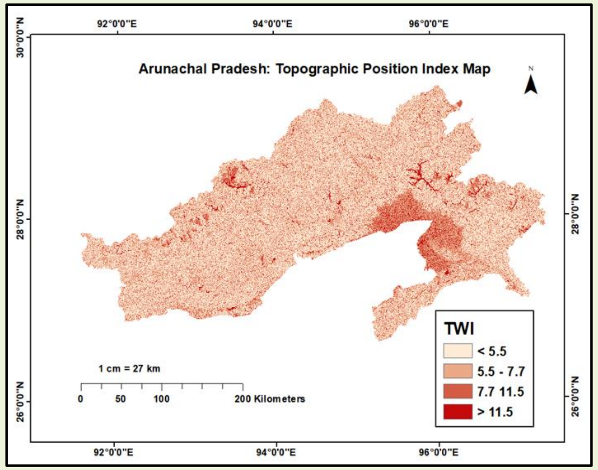
Stream Power Index (SPI)



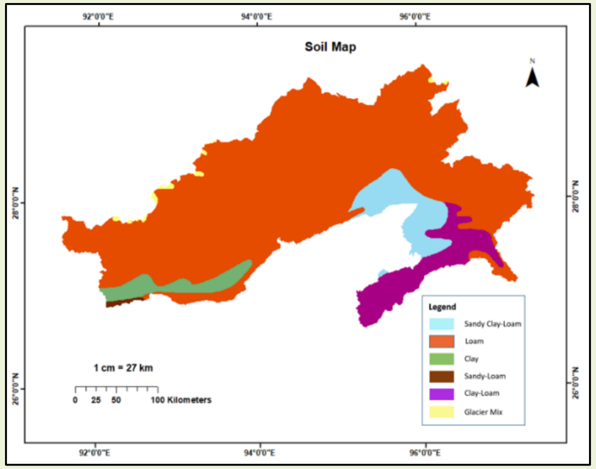
Profile Curvature



Plan Curvature

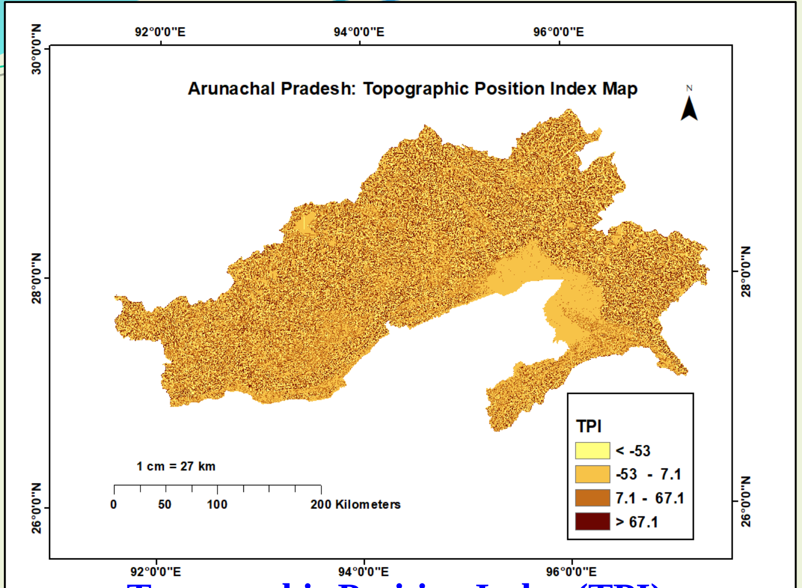


Topographic Wetness Index (TWI)

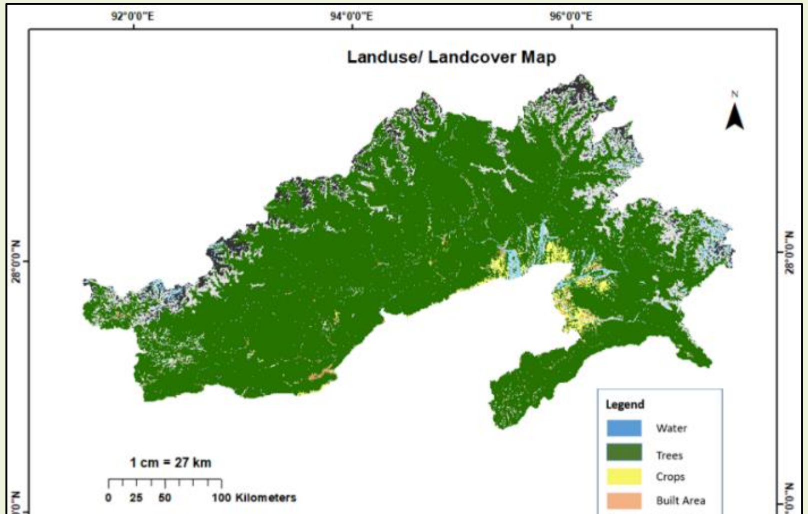


Soil Type

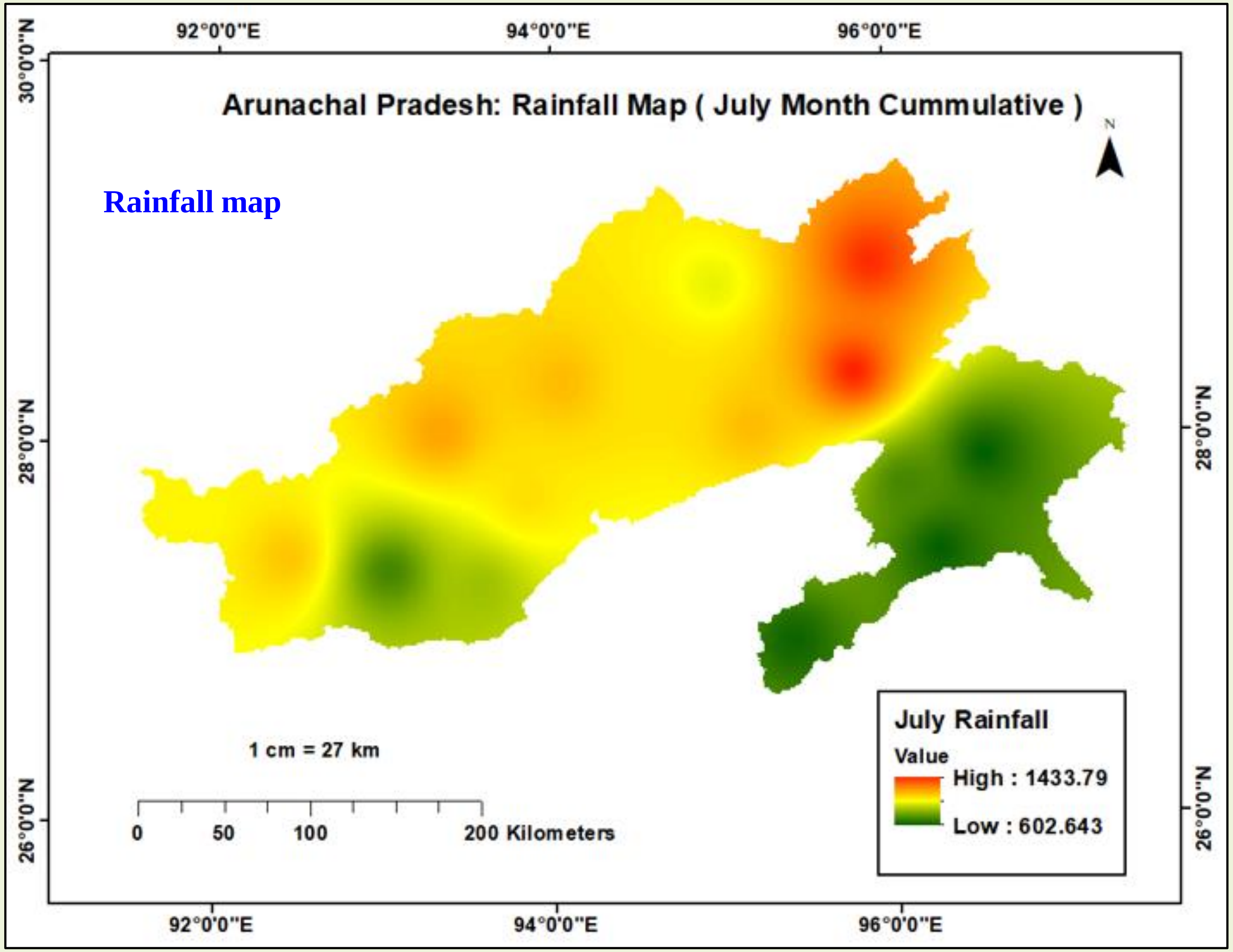
Collation of all Landslide Conditioning Factors



Topographic Position Index (TPI)

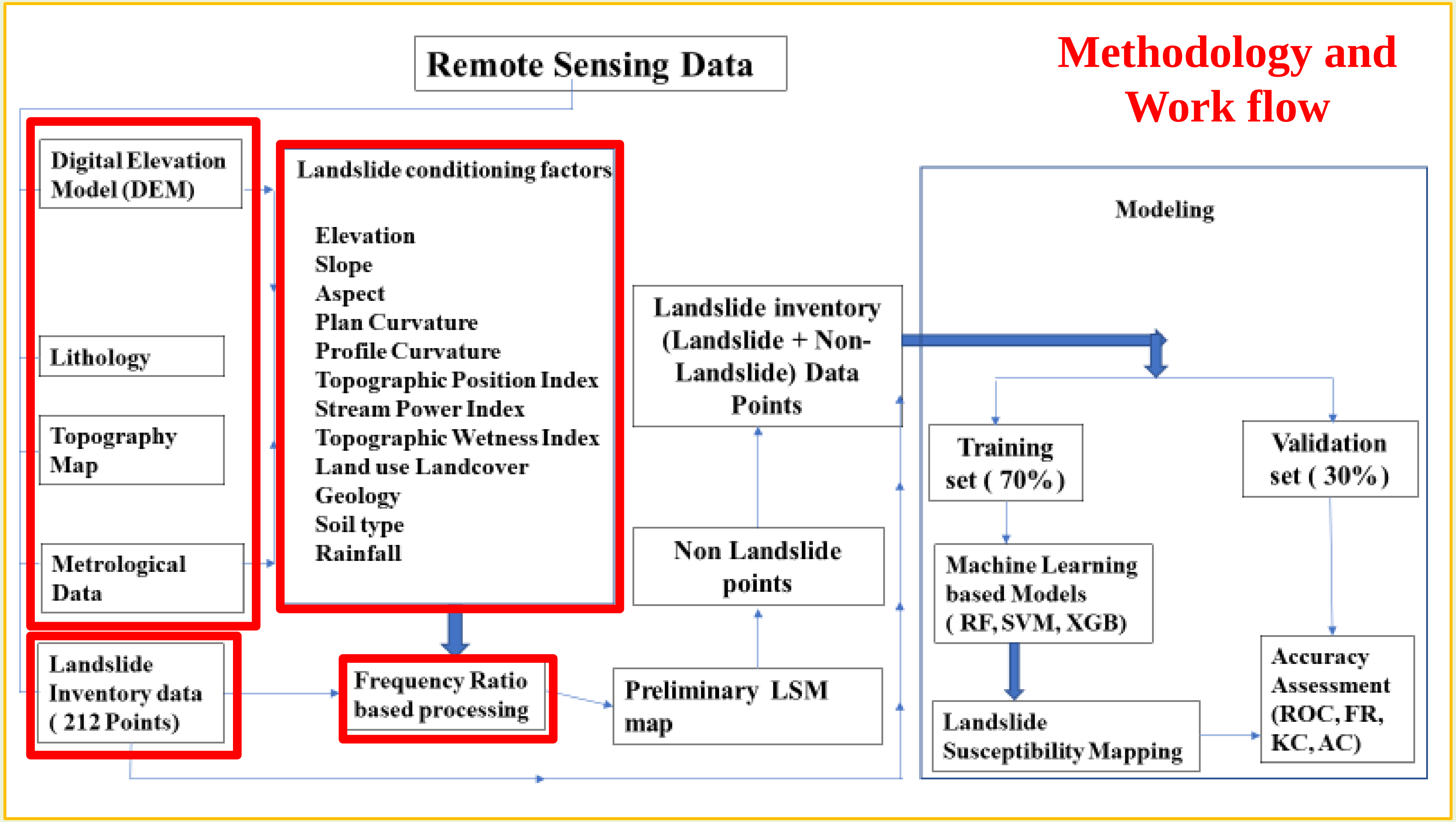


LULC



Rainfall map

Synergising Remote Sensing and ML to Landslide Susceptibility Assessment



Preparation of non-Landslide Points for Preliminary LSM

- **Frequency-Ratio Method (FR)**

- FR is a **ratio of the probability of presence and absence of landslide occurrences for each landslide conditioning factor class**
- **Higher FR value** indicates **stronger observed spatial relationship between the landslide occurrence and landslide conditioning factor**
- The FR values is converted into **Normalized Frequency Ratio values (NFR) in the range from 0.01 to 0.99** to facilitate the final analysis and interpretation
- Subsequently, **NFR values are used to reclassify all landslide conditioning factors for landslide susceptibility analysis**
- Lastly, **LSI is calculated based on the NFR values that have been determined in training process**

$$FR = \frac{P_i}{PL_i} = \frac{N_i^{pix}/N}{N_i^{Lpix}/N^L}$$

P_i: Percentage of pixels in each landslide conditioning factor class

PL_i: Percentage of landslide occurrence pixels in each landslide conditioning factor class pixel

N_i: Number of pixels in each landslide conditioning factor class

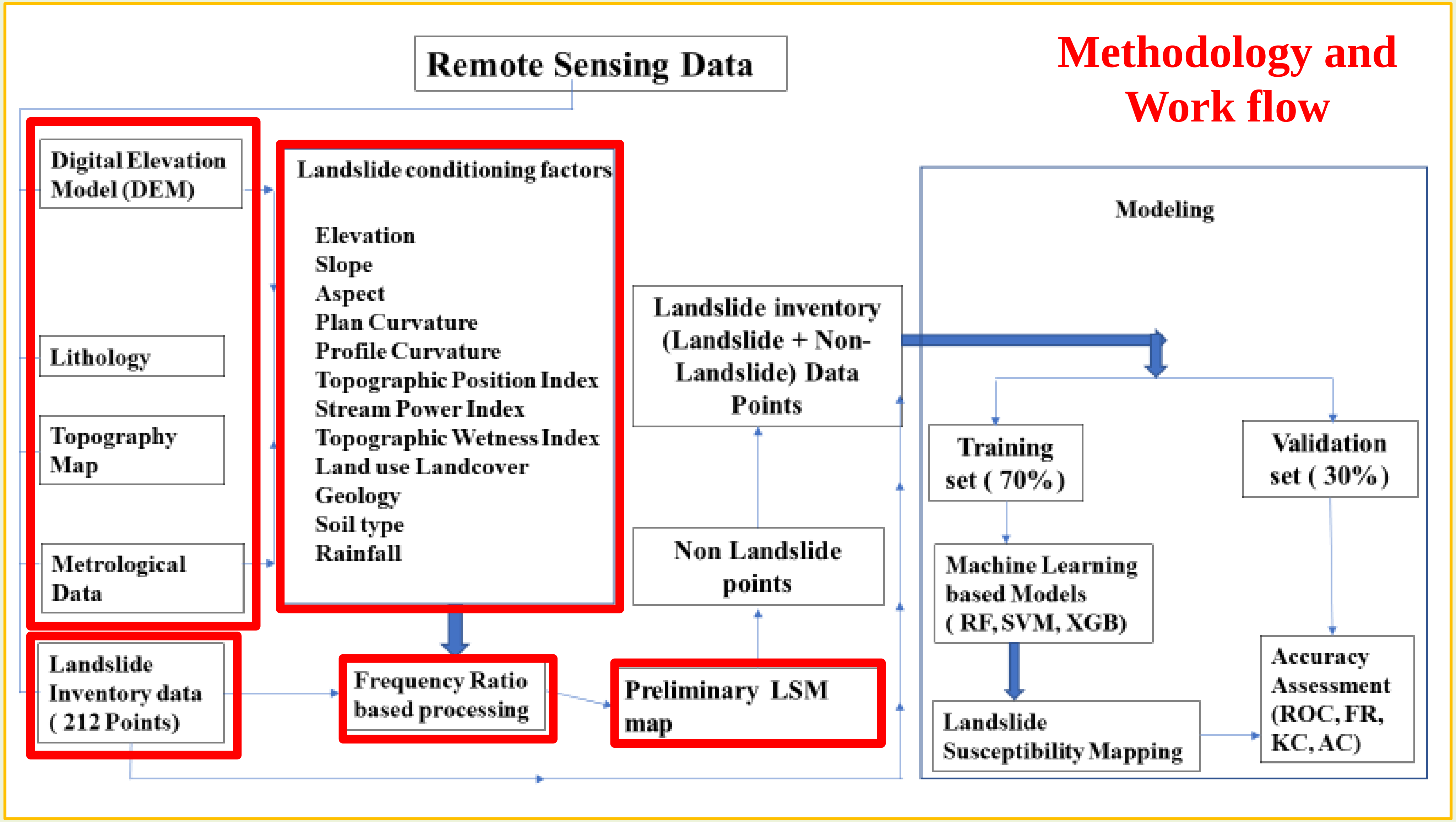
N: Number of all pixels in total the study area.

N^L: Number of all landslide occurrence pixels in total the study area

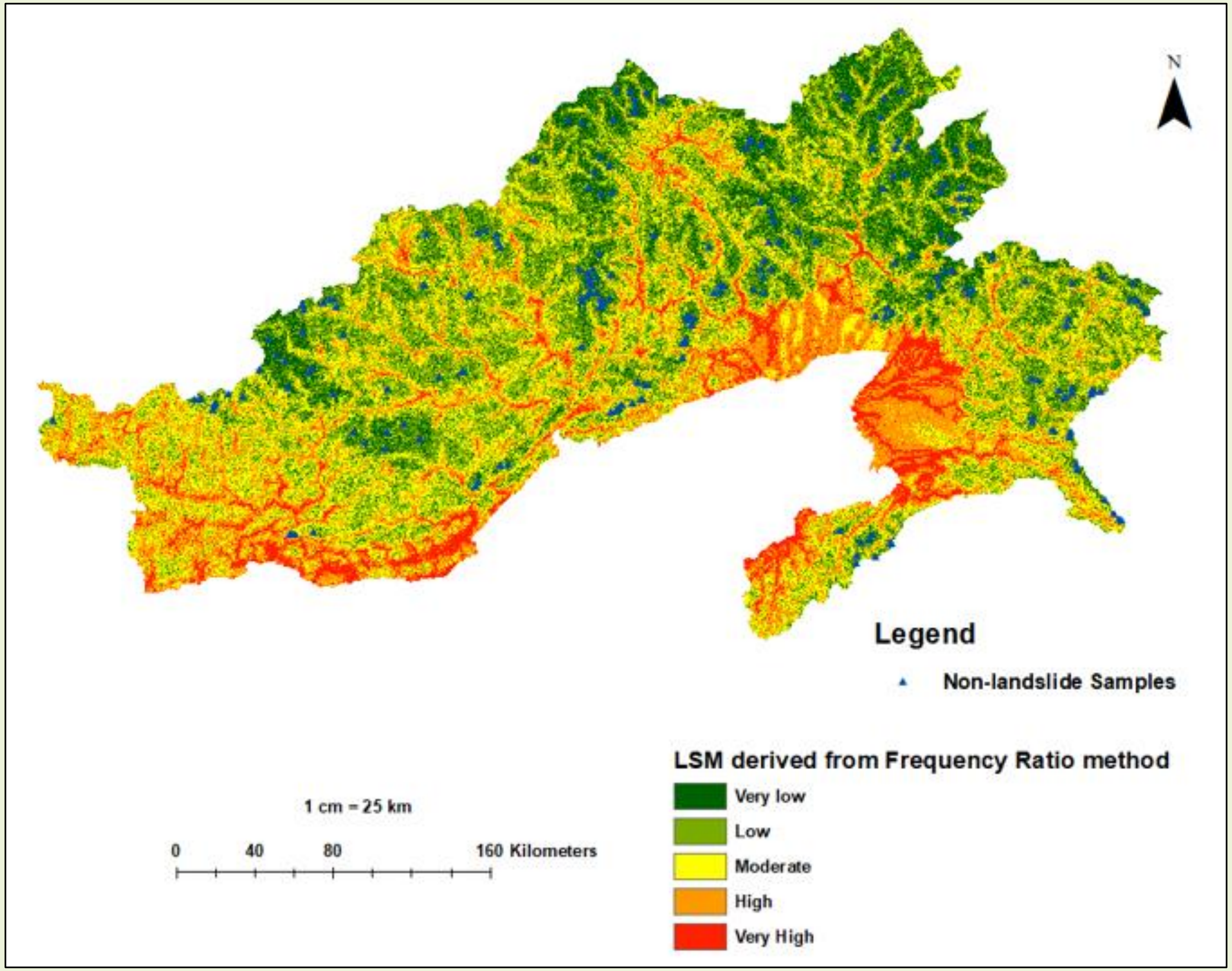
A Typical Example of FR Approach for ‘Slope’ LCF

SN.	Factors	Class	No. of Landslide	Landslide %	Area (No. of Pixel)	Area (%)	FR	Normalization
1.	Slope (Degree)	<5° (Gentle - Slope)	20	9.43	6715510	7.37	1.28	0.50
		5°-10° (Moderate Slope)	27	12.73	4558428	5.0	2.54	1.00
		10° - 16° (Strong Slope)	28	13.2	8355556	9.2	1.44	0.57
		16° - 25° (Very Strong Slope)	43	20.28	20580225	22.6	0.90	0.35
		25°-35° (Extreme slope)	49	23.11	27568745	30.3	0.76	0.30
		35° - 45° (Steep Slope)	34	16.03	17607238	19.3	0.83	0.33
		>45° (Very Steep Slope)	11	5.18	5751399	6.3	0.82	0.32
		Summation	**212**		**91137101**	**100**		

Synergising Remote Sensing and ML to Landslide Susceptibility Assessment

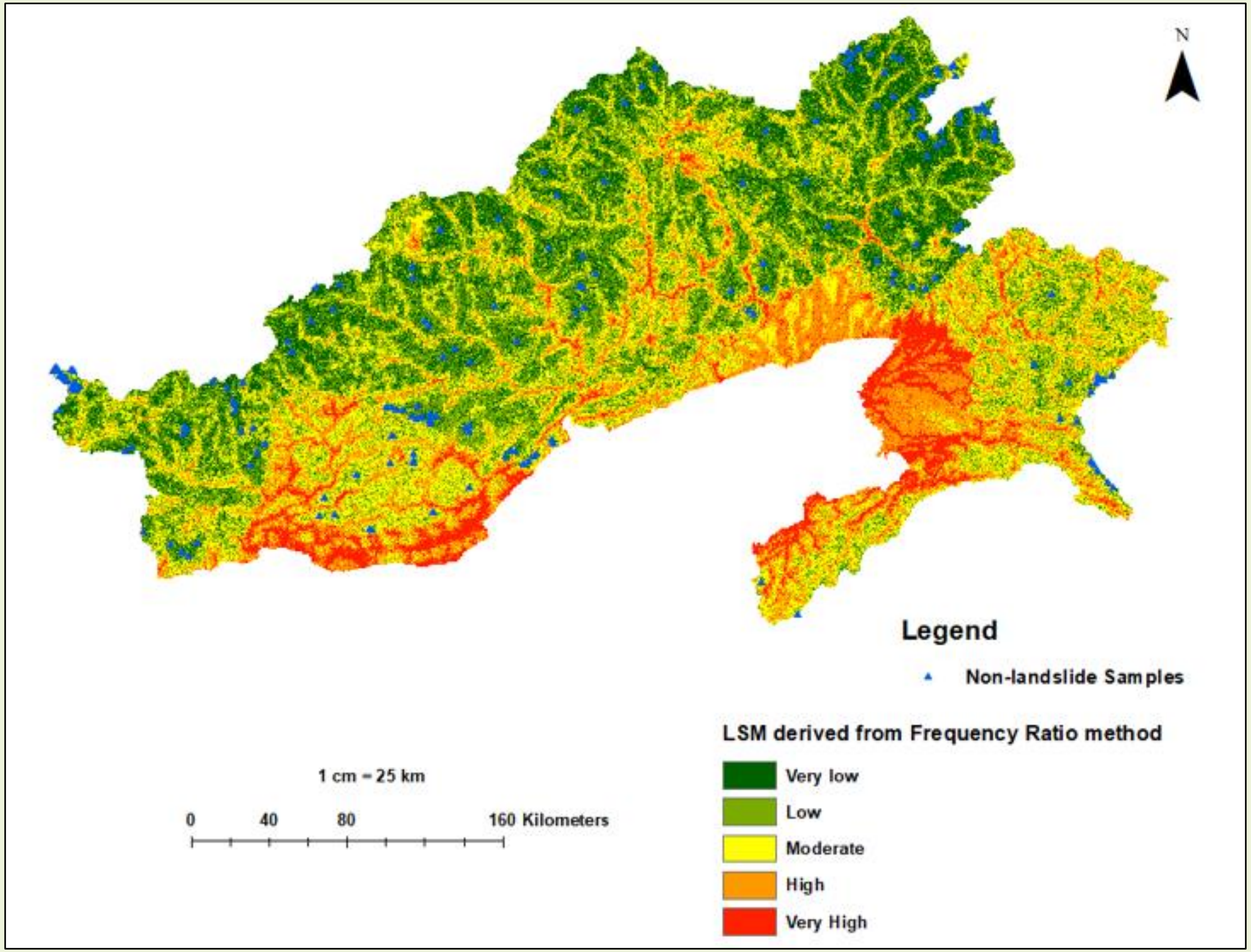


Preliminary Landslide Susceptibility Mapping of Arunachal Pradesh



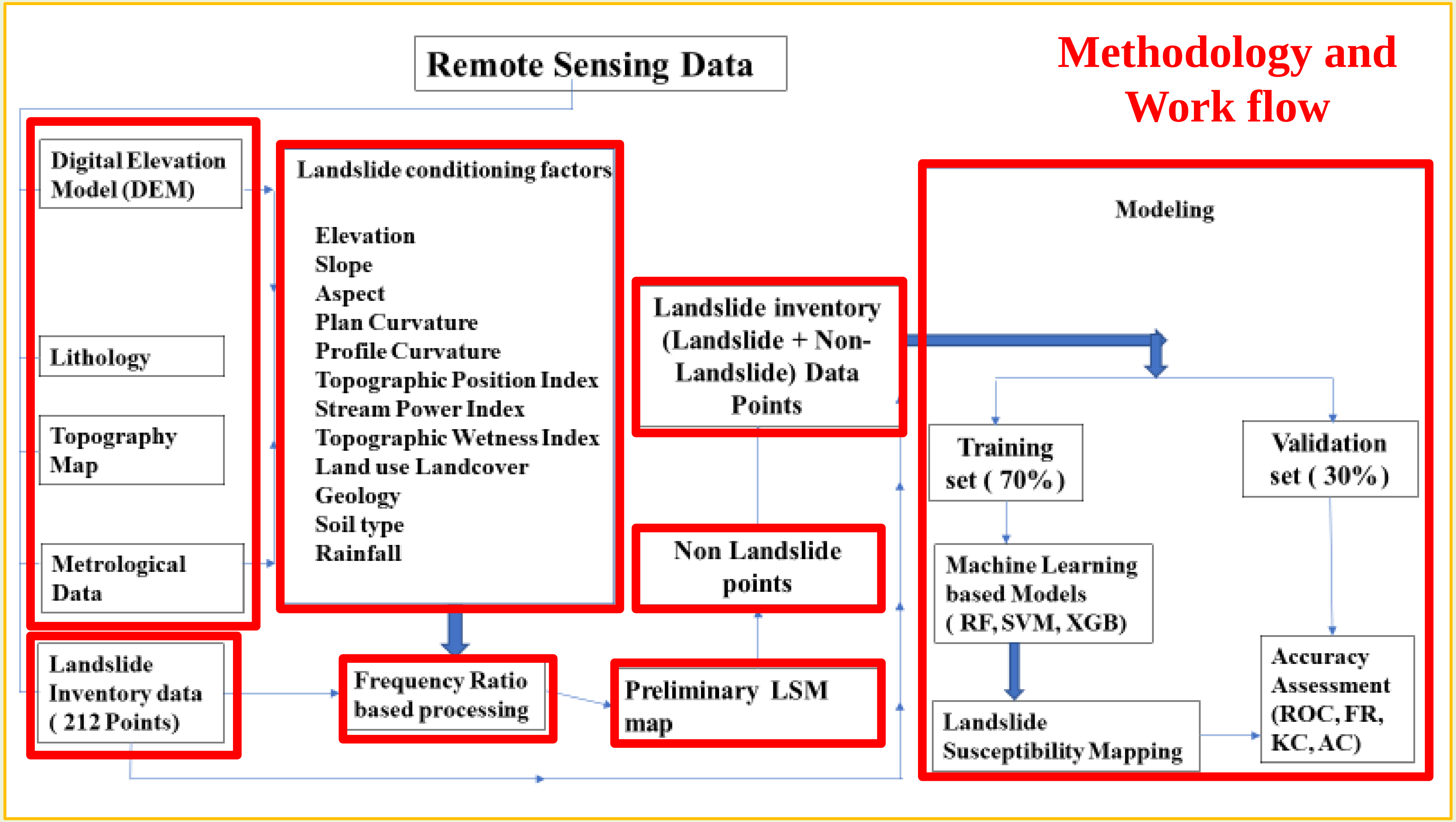
Landslide susceptibility map of the study area obtained from the frequency ratio method for July month

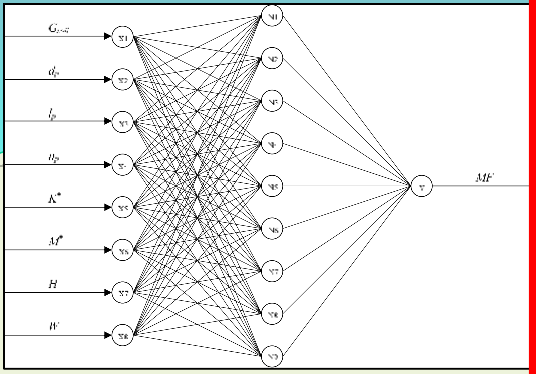
Preliminary Landslide Susceptibility Mapping of Arunachal Pradesh



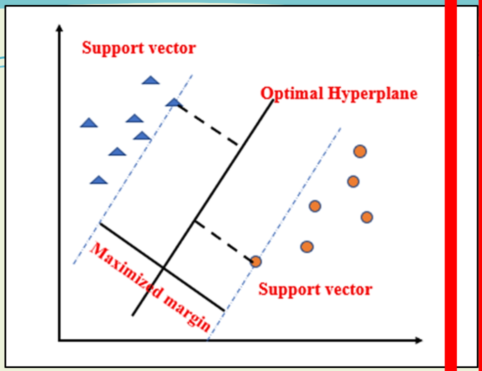
Landslide susceptibility map of the study area obtained from the frequency ratio method for December month

Synergising Remote Sensing and ML to Landslide Susceptibility Assessment

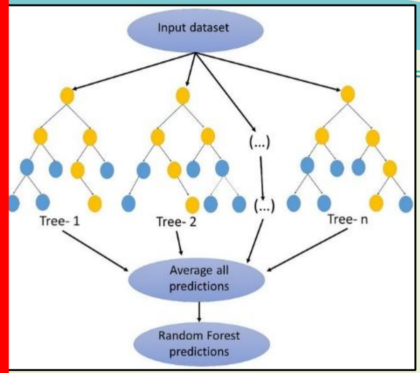




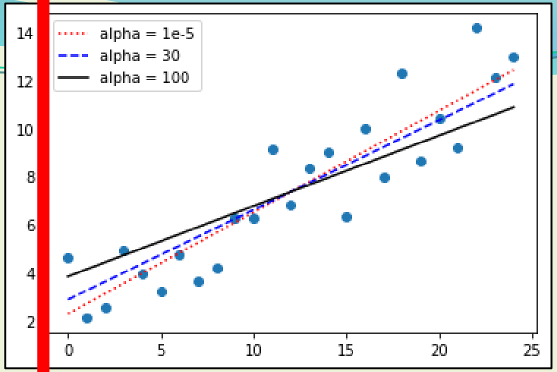
ANN



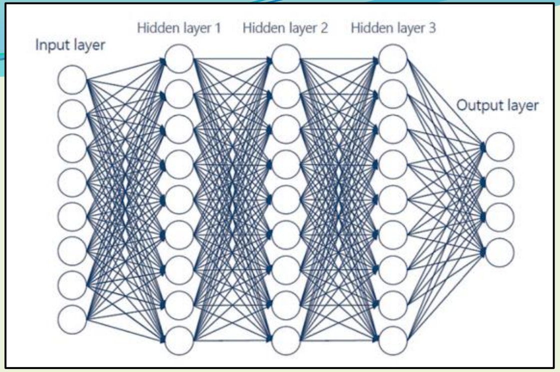
SVM



RF



RR

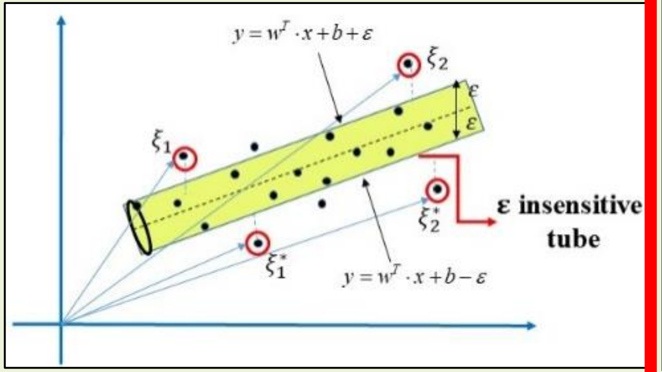


DNN/DL

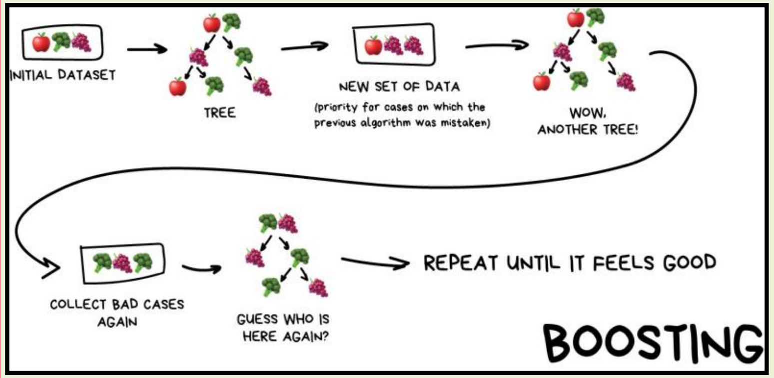
AI /ML are Data-Driven TOOLS for Mapping and Prediction

Why to use? Where to integrate? Are we intelligently using it?

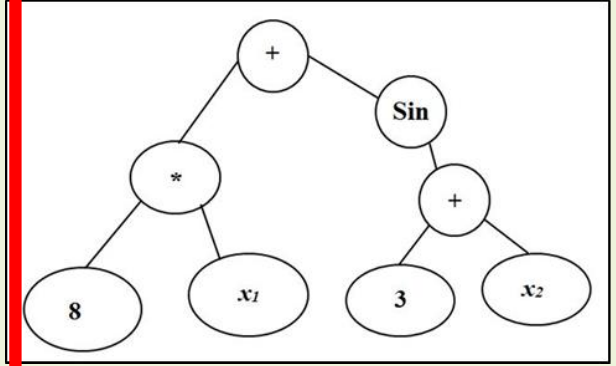
The PHYSICS and ENGINEERING of the problem is MORE IMPORTANT

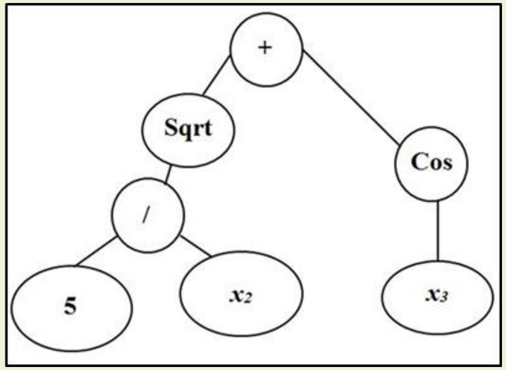


SVR



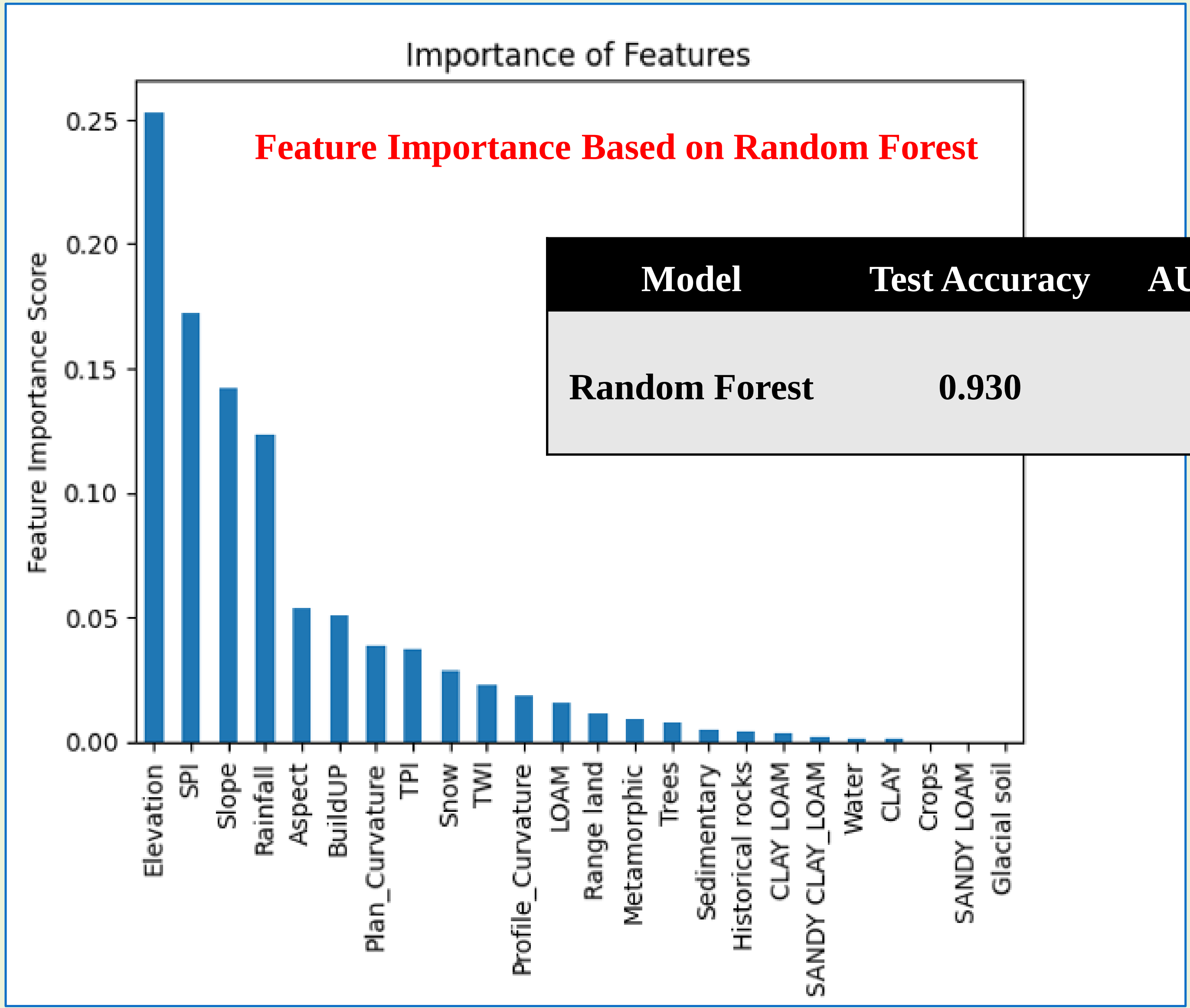
GB/GBRT/XGBOOST





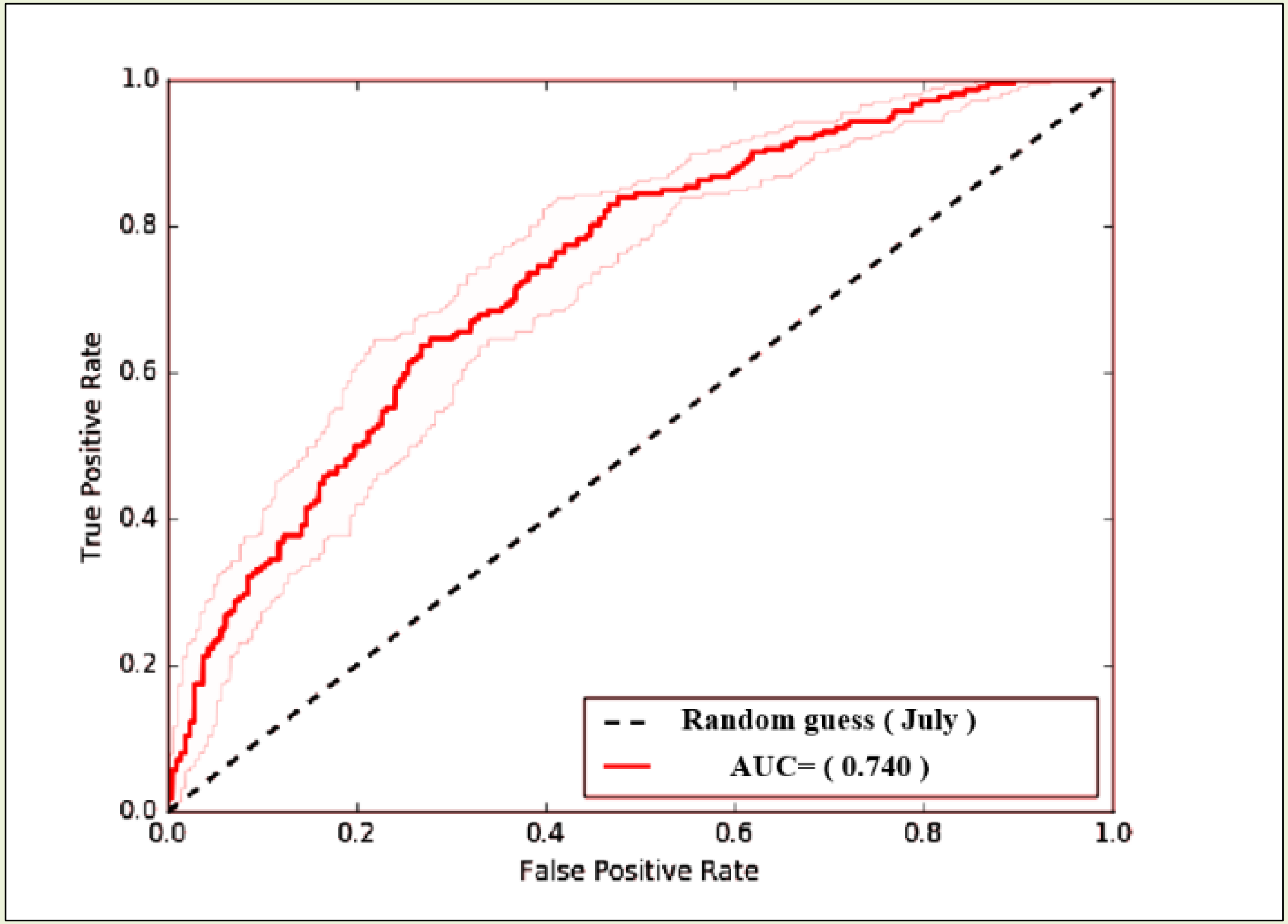
GP/MGGP

Feature Importance



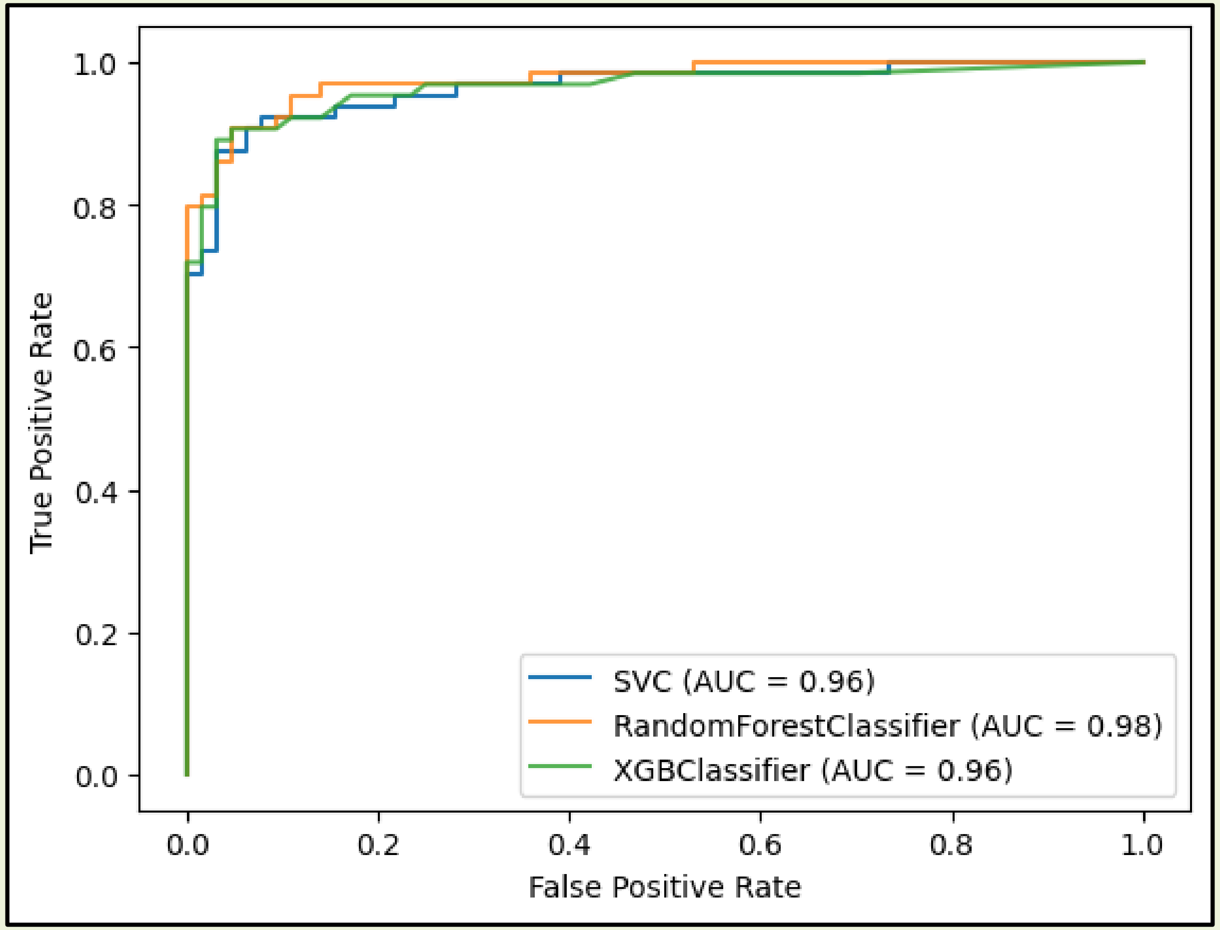
Model	Test Accuracy	AUC (%)	RMSE	MAE	Kappa Coefficient
Random Forest	0.930	98.0	0.265	0.07	0.859

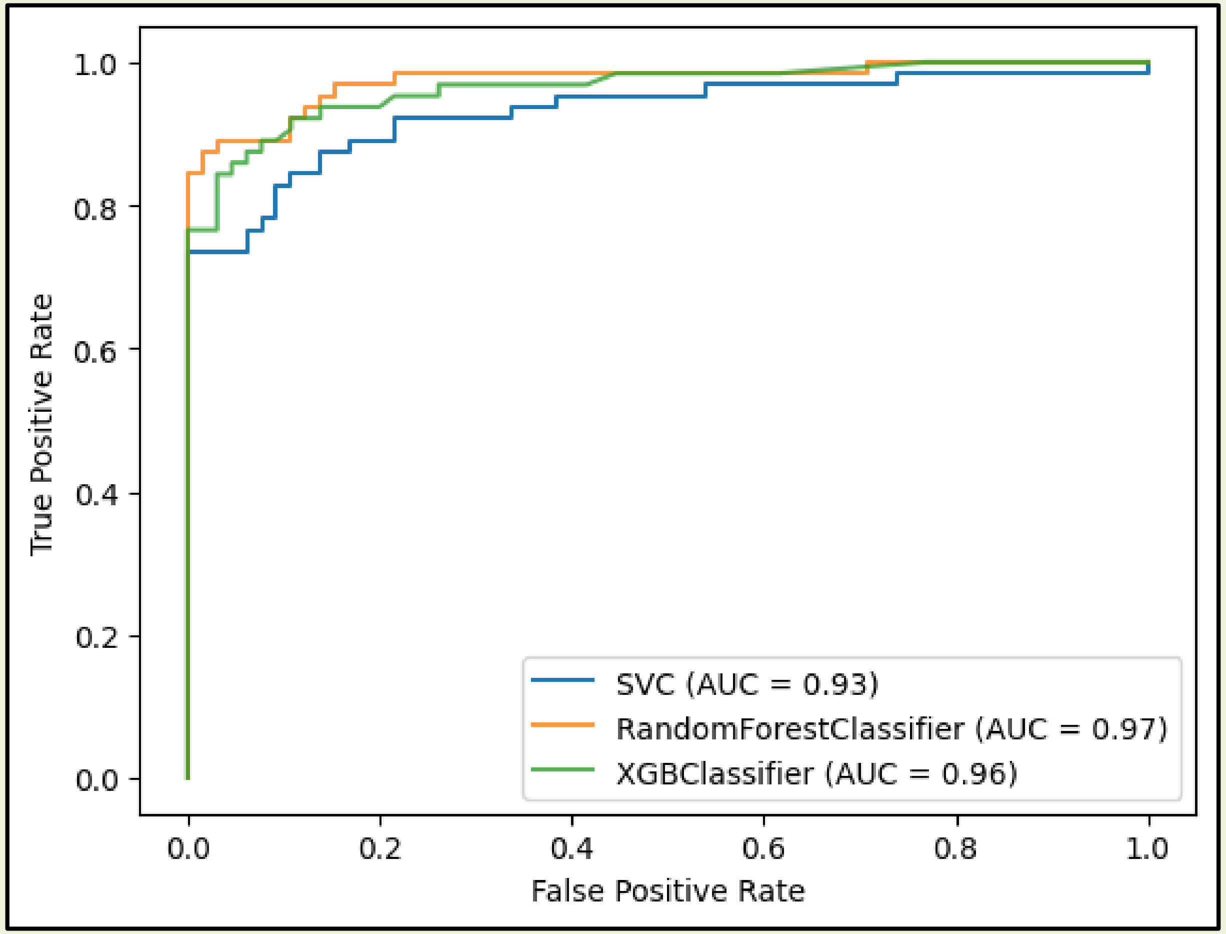
Receiver-Operator Characteristics (ROC) Curve



Prediction rate curves for the susceptibility maps produced using frequency ratio method considering July month rainfall

Receiver-Operator Characteristics (ROC) Curve

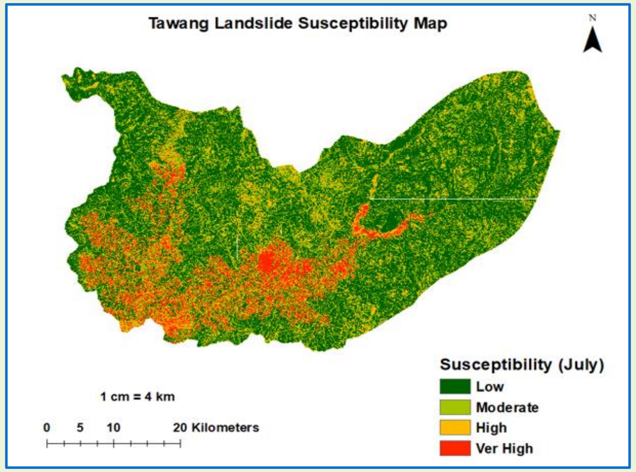


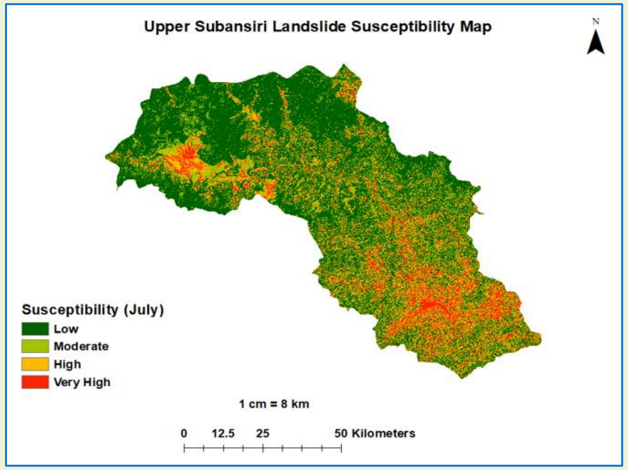


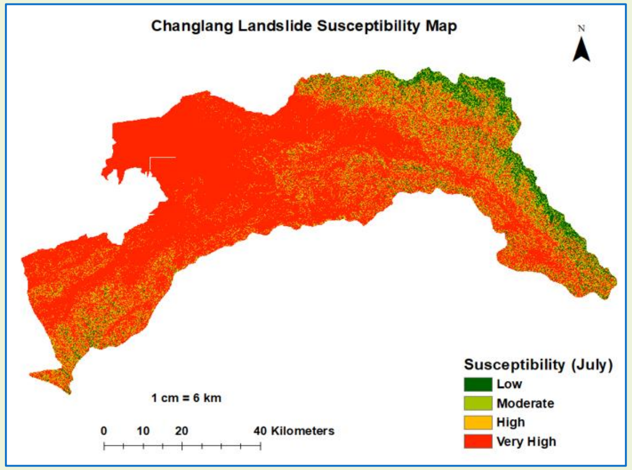
ROC curve Analysis with AUC score of the ML models for July month using validation dataset

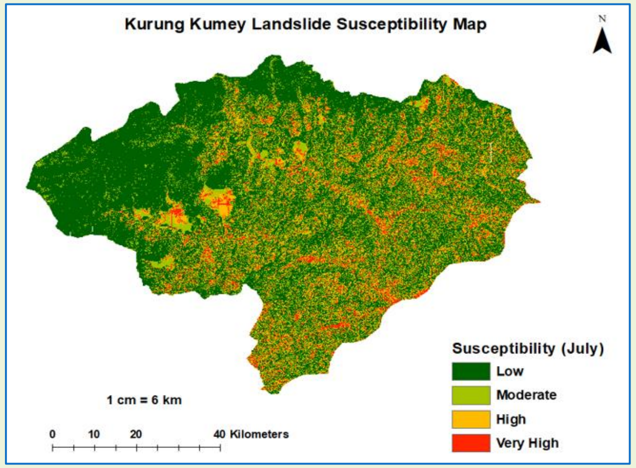
ROC curve Analysis with AUC score of the ML models for December month using validation dataset

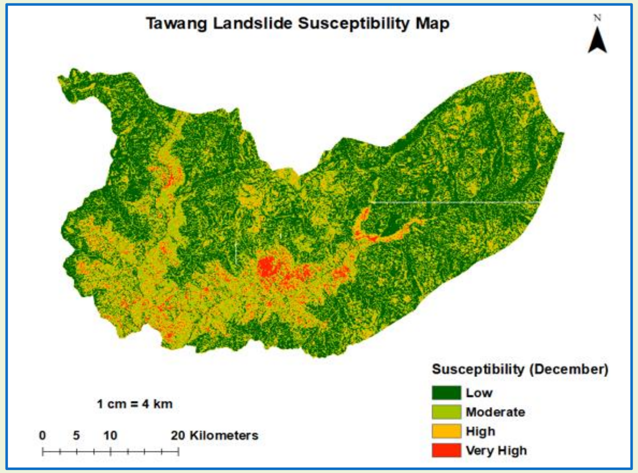
District-wise LSM of Arunachal Pradesh: RF Model

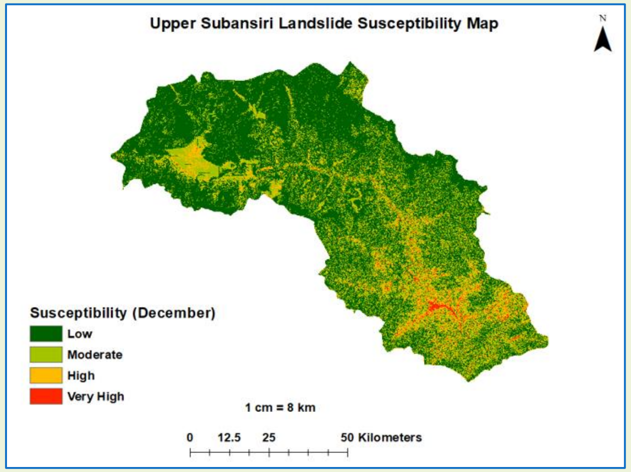


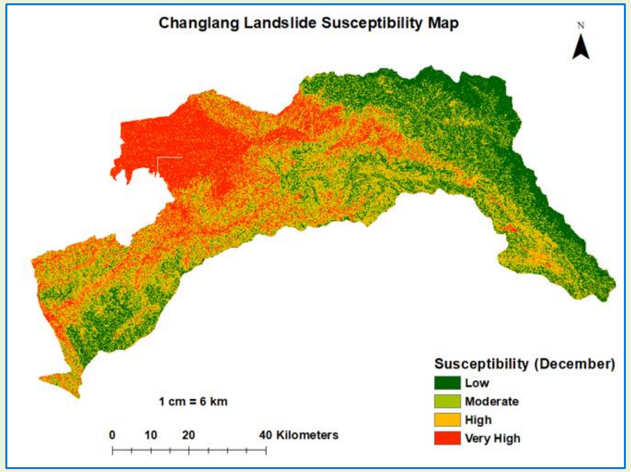


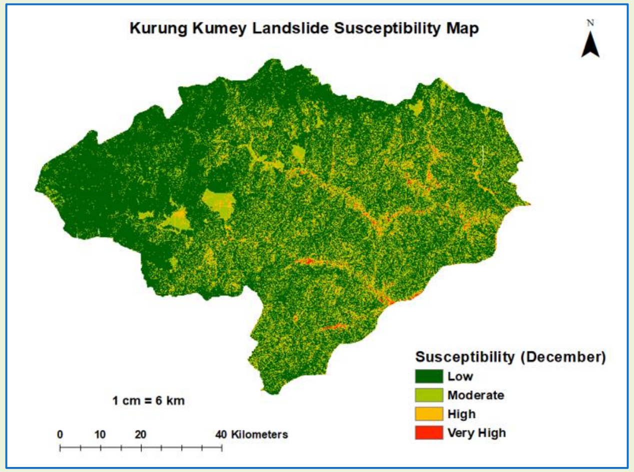






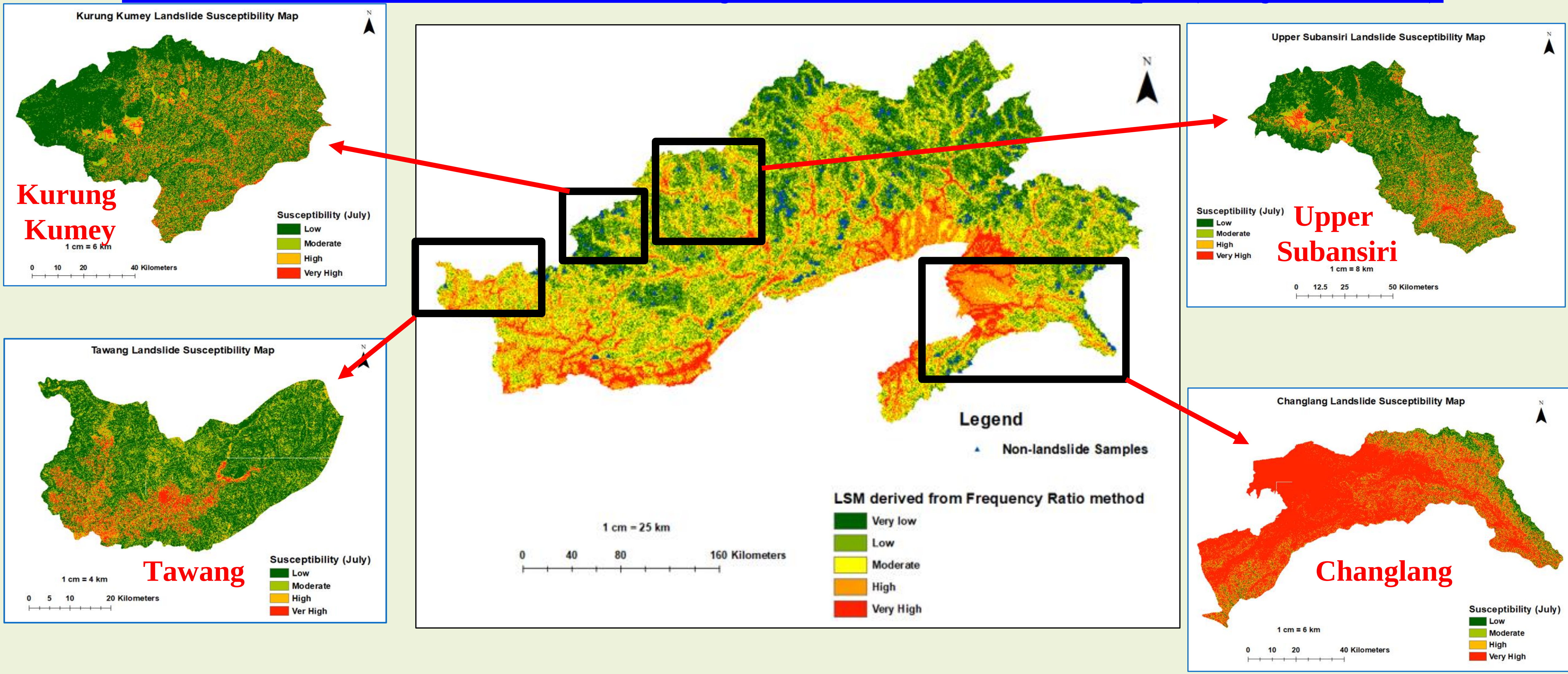




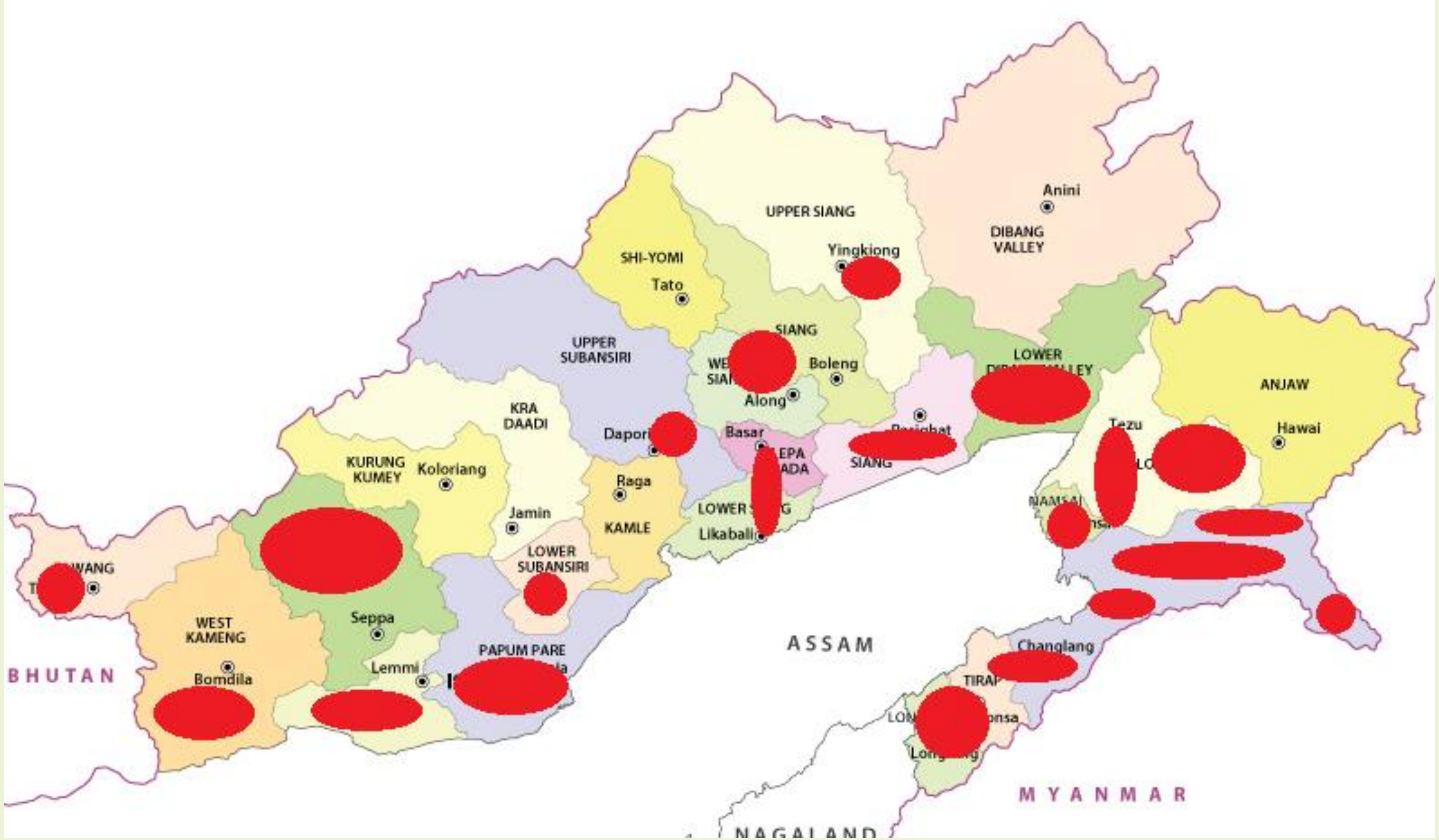


Tawang **Upper Subansiri** **Changlang** **Kurung Kumey**

Difference between Preliminary and Final LSM Maps (July Month)



Rainfall-Induced Landslide Susceptible Regions of Arunachal Pradesh

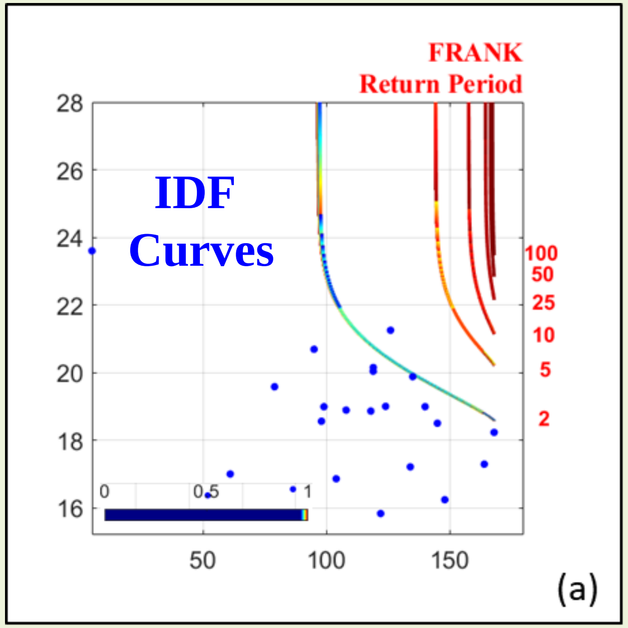


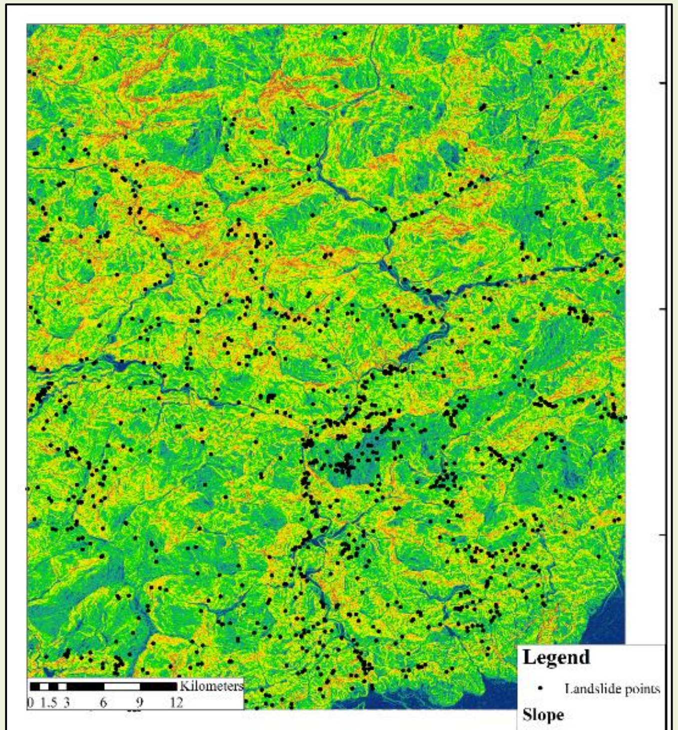
Major Inferences from LSM of Arunachal Pradesh

- **Development of Landslide Susceptibility Mapping of Arunachal Pradesh**
  - Integration of frequency ratio approach and machine learning method
    - Effective way to develop LSMs of an area, thereby providing a comprehensive and advanced approach to geohazard analysis.
  - Frequency Ratio (FR) method is efficient
    - Selecting the best possible non-landslide points selection for constructing the preliminary LSM
  - For this regions, RF technique is found to be the most efficient in developing final LSM
    - With a test accuracy of 93%, the ROC-AUC was achieved to be 98%, while the RMSE, MAE and Kappa coefficient were obtained to be 0.265, 0.07 and 0.859, respectively
      - Exhibiting magnitudes that are indicative of a very reliable and superior prediction of the landslides in the region
  - Major challenges in developing a reliable LSM for Arunachal Pradesh
    - Scarcity of historical landslide data, limited data on local geological conditions, inadequate monitoring and the absence of a robust early warning system

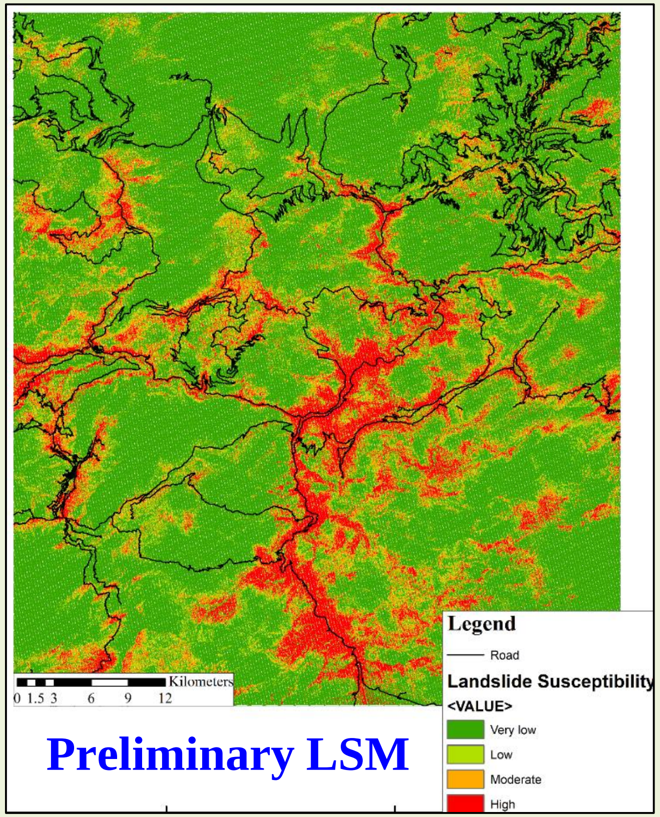
Landslide Susceptibility Mapping of Sikkim

- **Construction of a major and strategic railway line**
  - ❖ Sevoke-Rangpo (Phase-1)
  - ❖ Rangpo-Gangtok (Phase-2)
  - ❖ Gangtok to Indo-China Border (Phase-3)
    - Lot of anthropogenic activities
    - Several rainfall-induced landslides

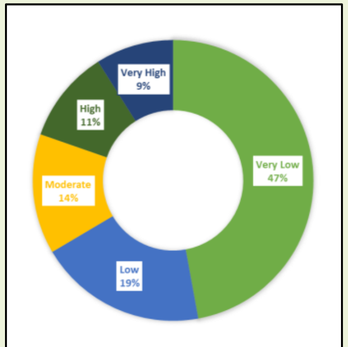




Landslide Inventory



Preliminary LSM



Percentage of area under each susceptibility class

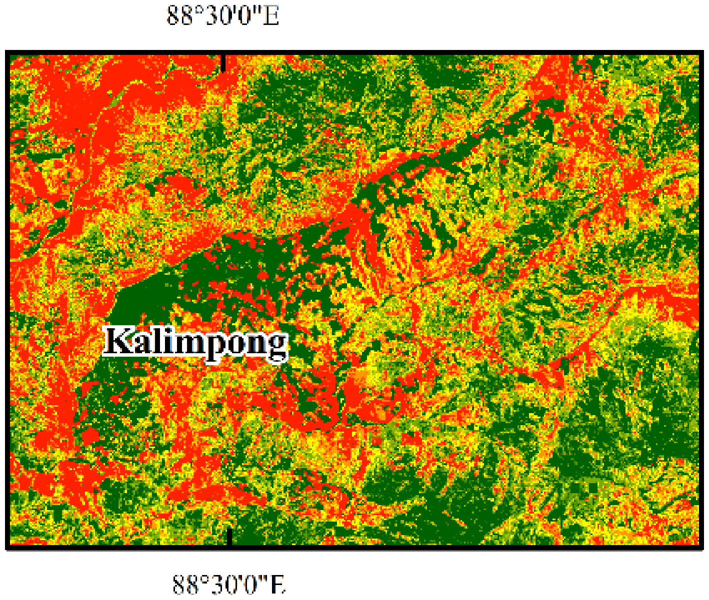
Performance of ML Models: Spatial Heterogeneity in LSM

ML Model	Test Accuracy		Test RMSE		Test Loss		AUC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CoNET-RNN	0.8385	0.0115	0.3500	0.010	0.4341	0.0250	0.92	0.01
CoNET-LSTM	0.8093	0.0137	0.3713	0.012	0.4501	0.0355	0.89	0.01
CoNET-GRU	0.8011	0.0215	0.3796	0.020	0.4757	0.0547	0.89	0.03

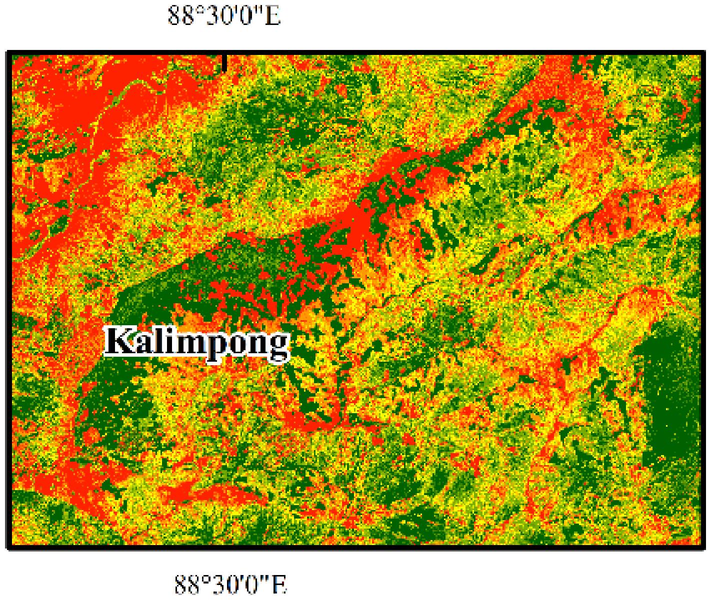
Performance metrics not so dissimilar

Notable spatial variability in LSM

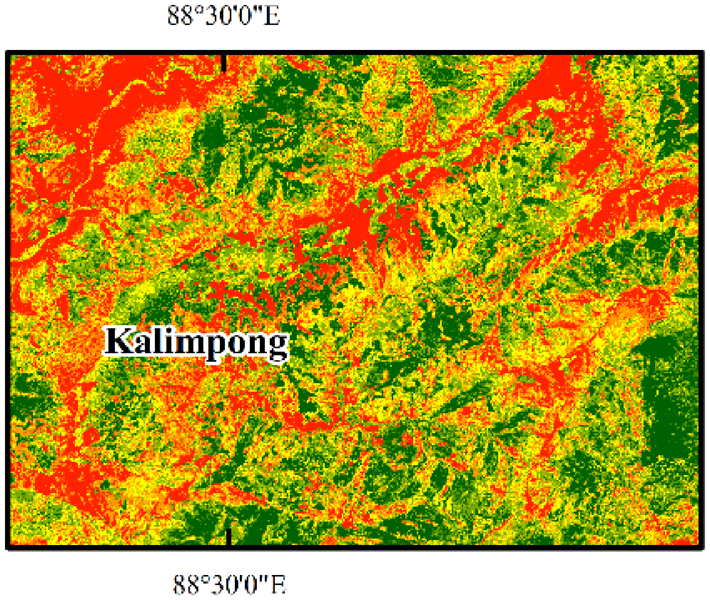
CoNet-RNN



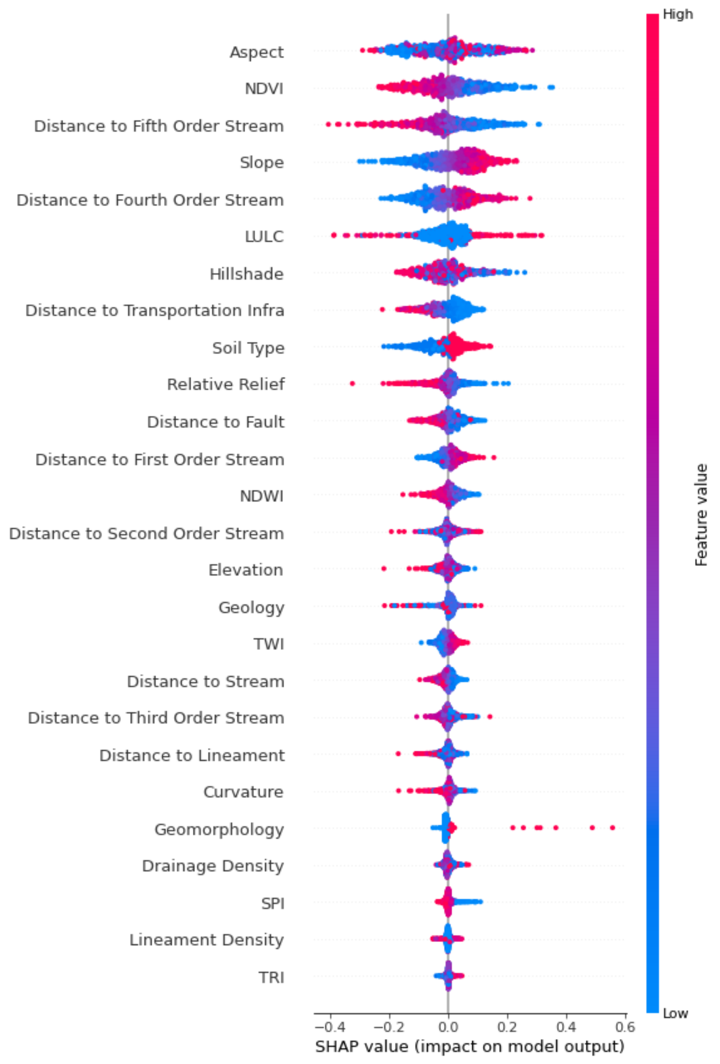
CoNet-LSTM



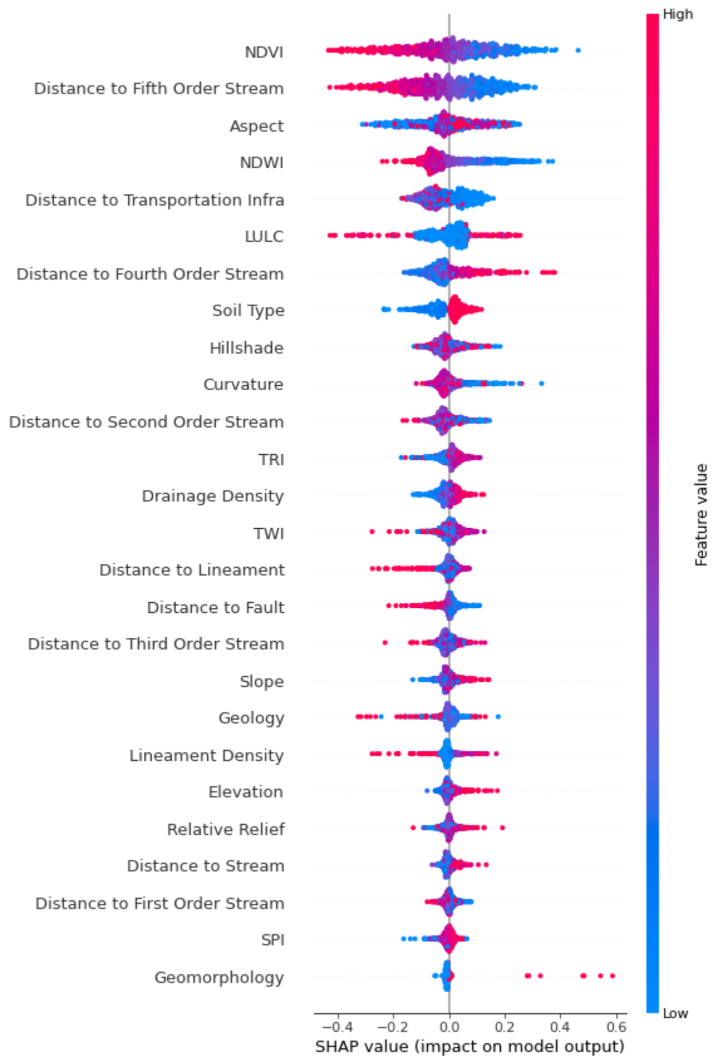
CoNet-GRU



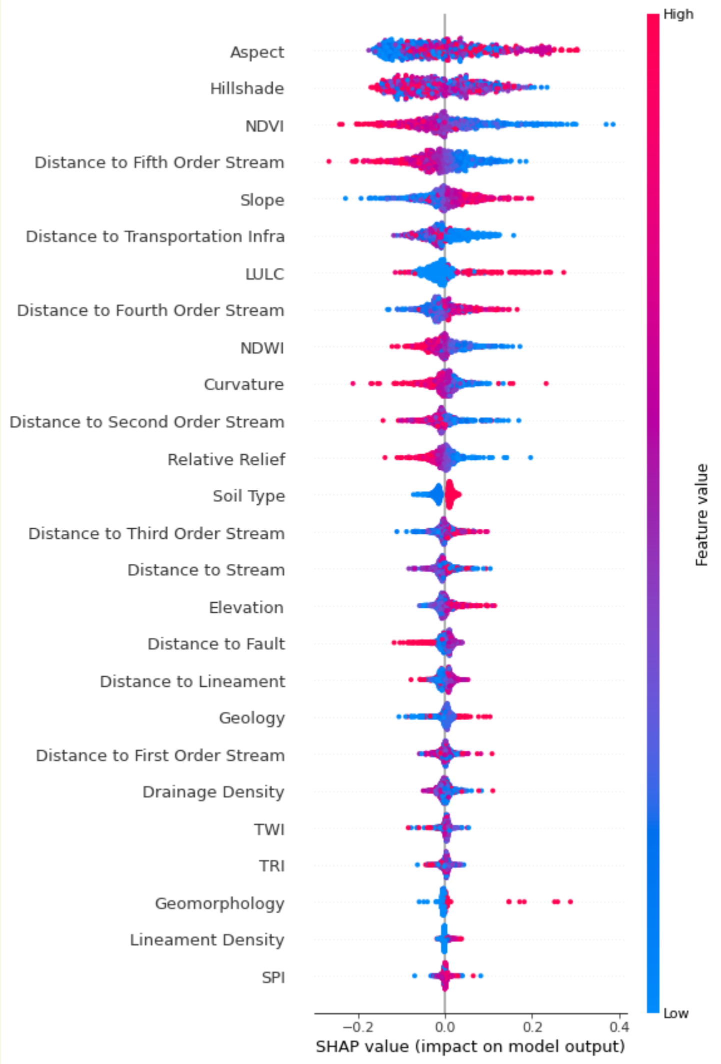
Model Interpretability: Shapley's Additive Explanation (SHAP plots)



CoNet-RNN

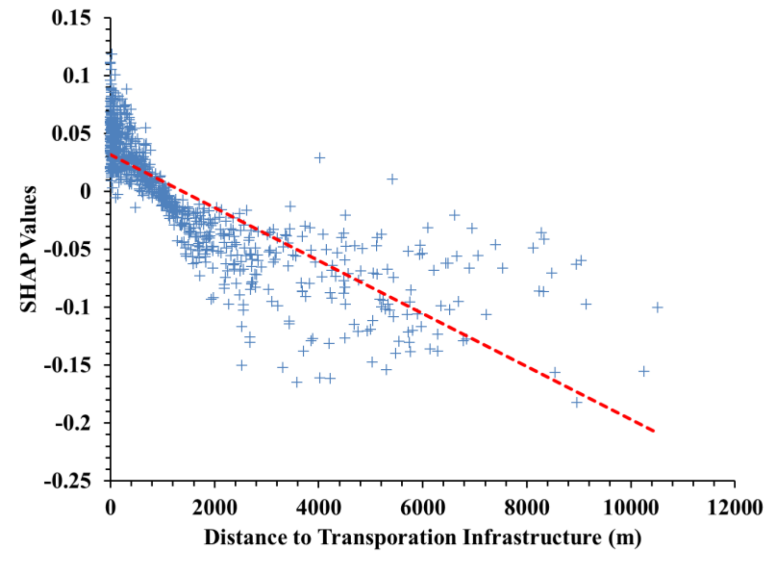


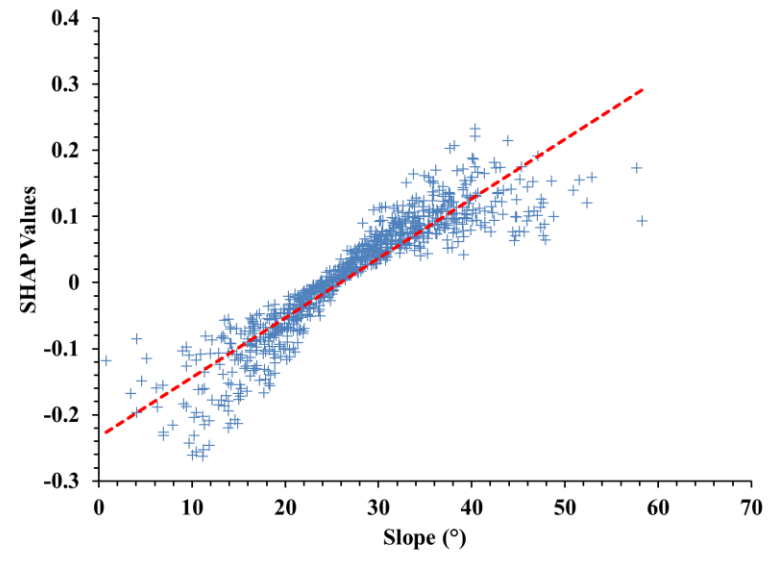
CoNet-LSTM

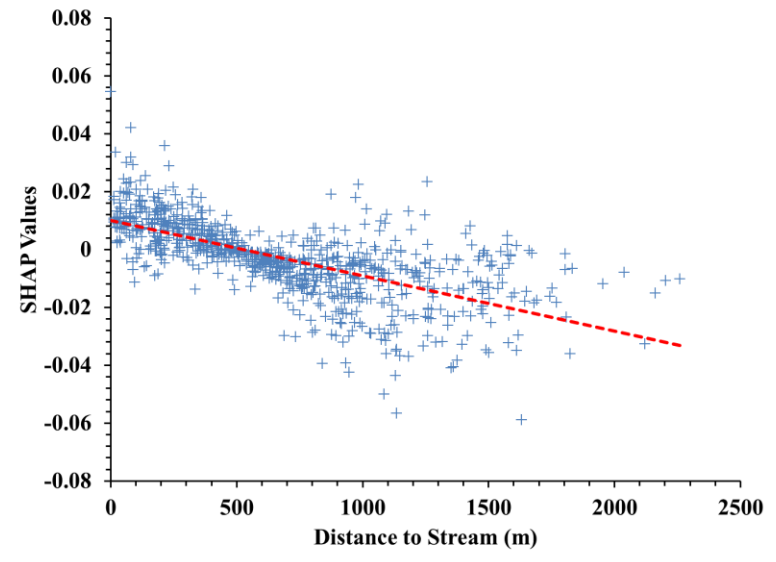


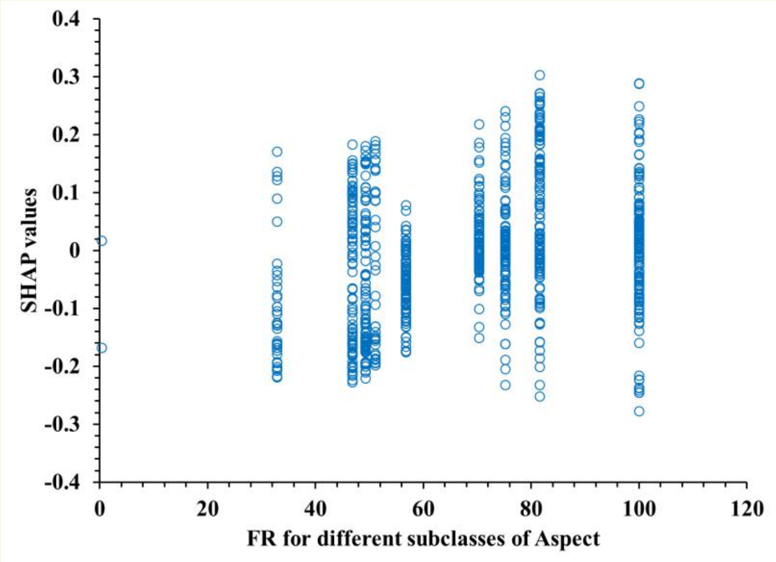
CoNet-GRU

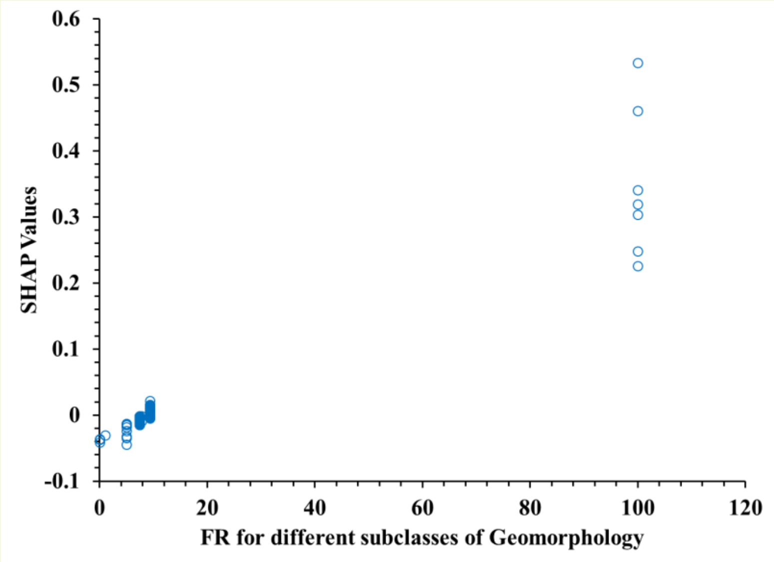
Model Interpretability: SHAP Dependence plots





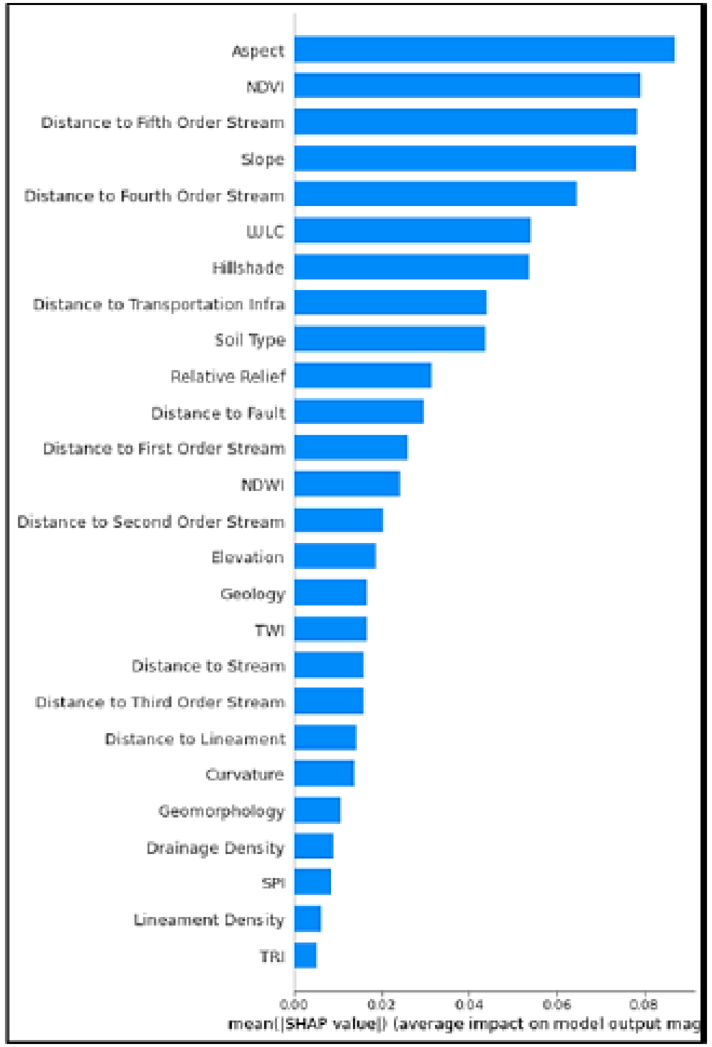




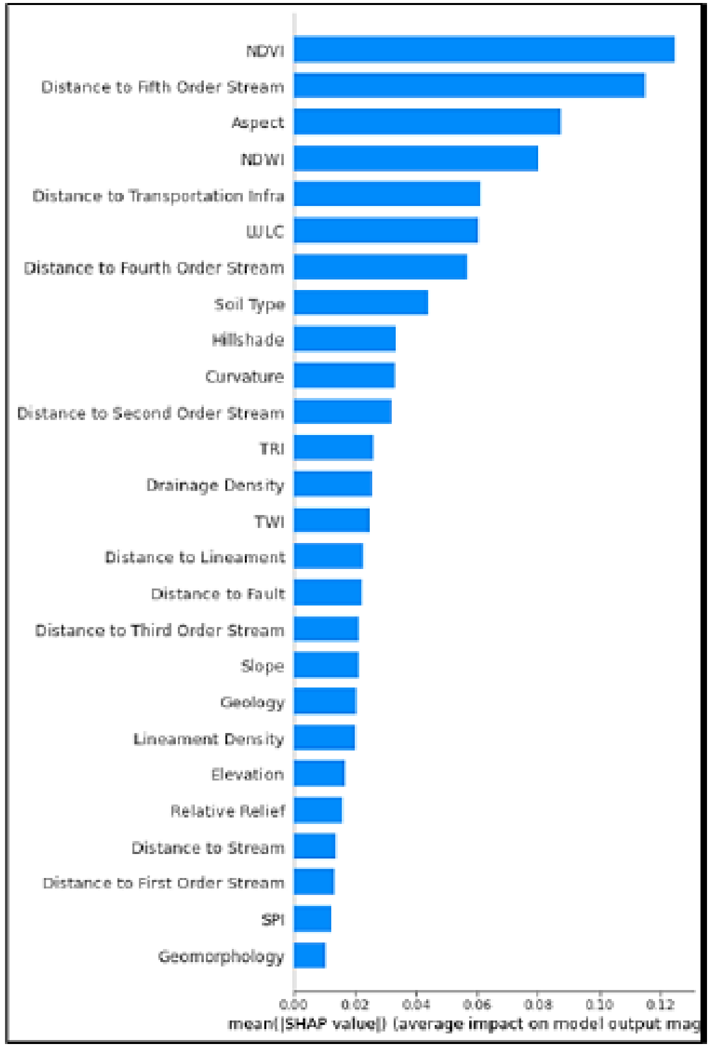


Feature	Value
Slope	> 25°
Distance to transportation infrastructure	< 1000 m
Distance to stream	< 500 m

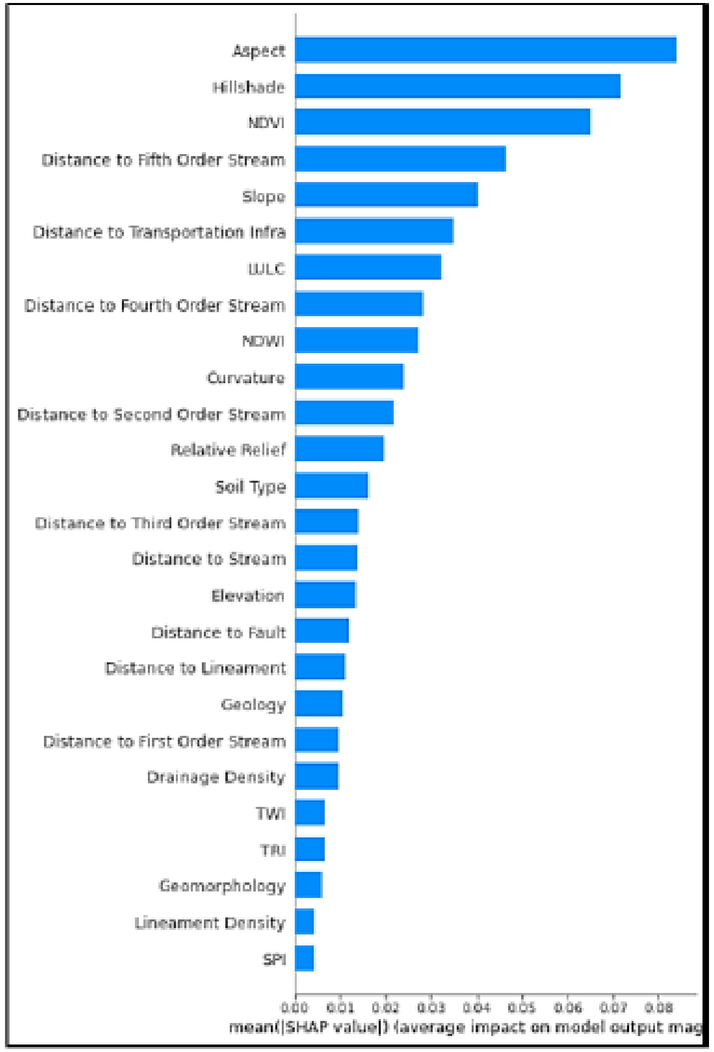
Model Interpretability: Feature Importance



CoNet-RNN

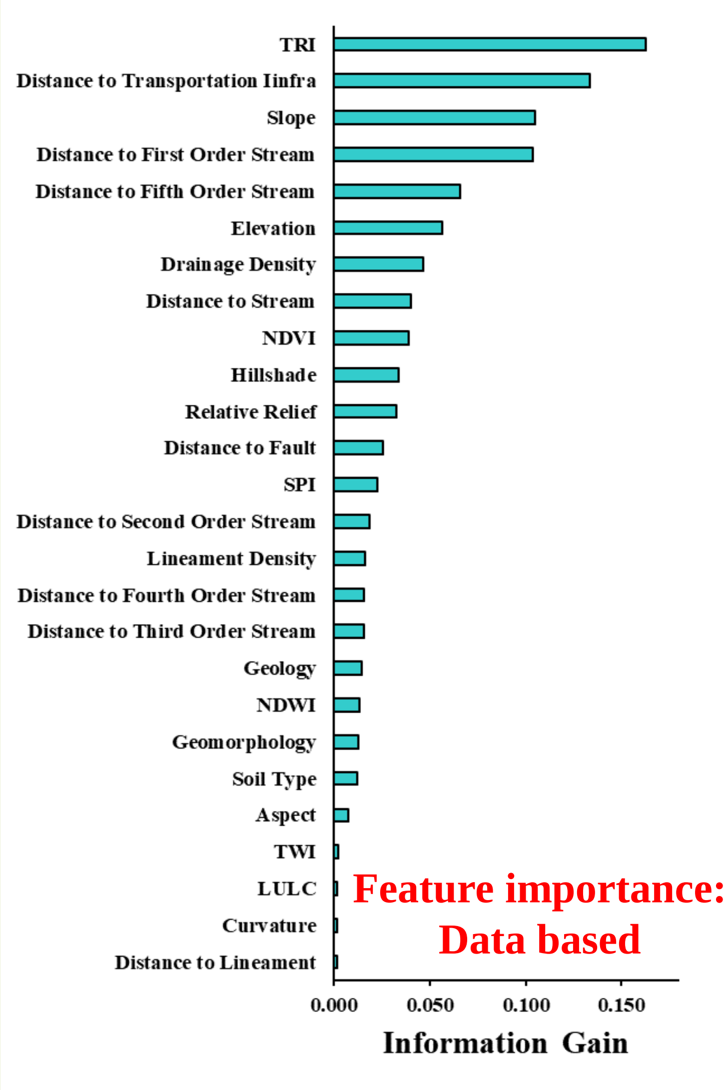


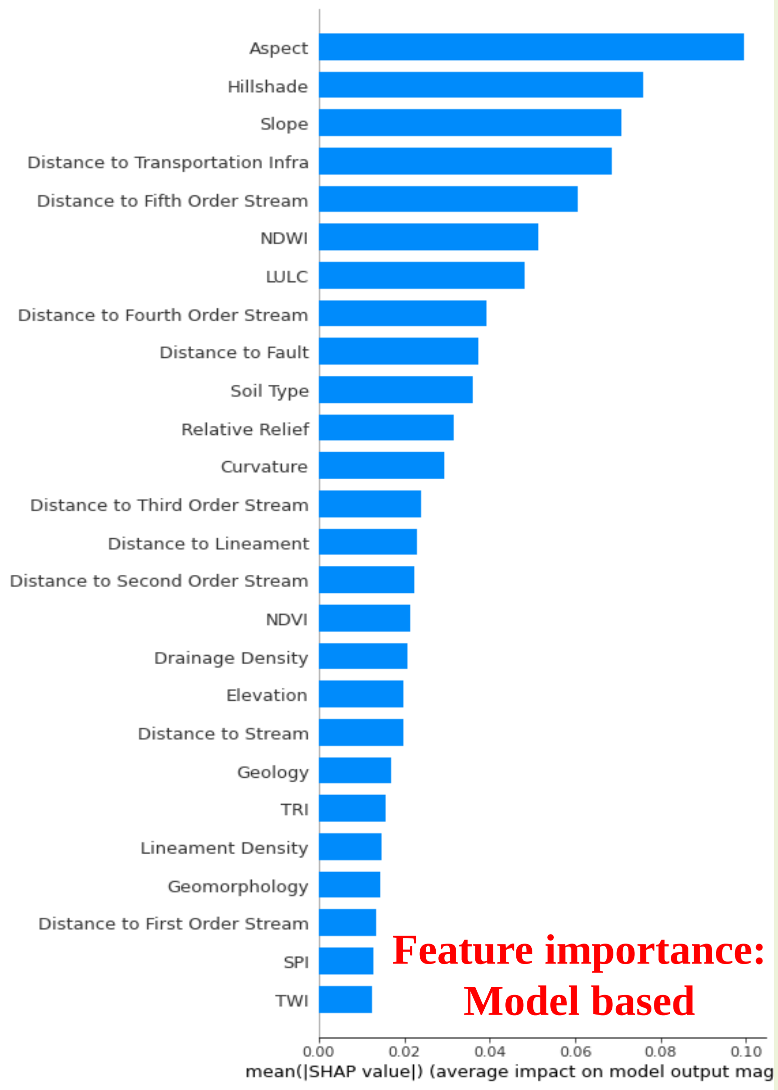
CoNet-LSTM



CoNet-GRU

CRITICAL FINDING

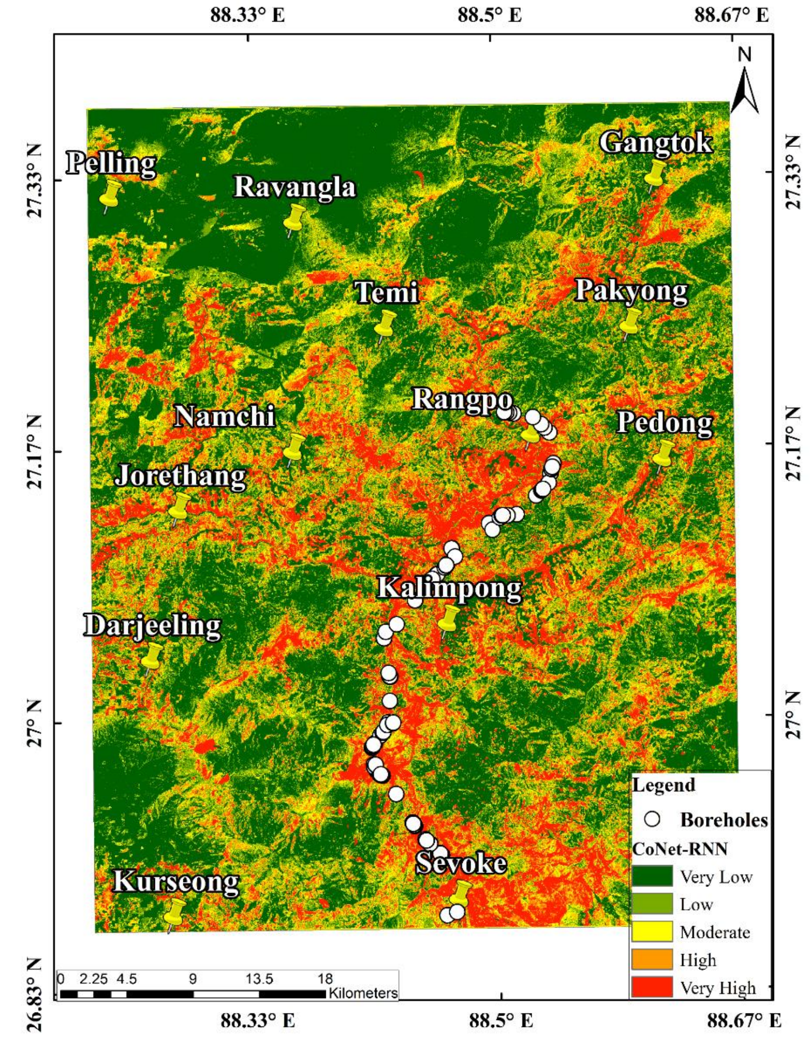




Complex inter-relation between features might not be properly interpretable if only data-based approach is used such as the Information Gain (IG) method

Essence of Engineering Analysis: Geotechnical Investigations

- **Borehole data from 124 locations was collected**
- **Properties collected from the geotechnical investigation report**
  - Soil description
  - Overburden depth
  - In-situ coefficient of permeability
  - Ground water table depth
  - Particle size distribution
  - Natural water content
  - Bulk and dry density
  - Shear strength parameters



Geotechnical Investigations: Typical Borelogs

Location : N 2978023 E 645014 — Ground Elevation : +179.3m
Method of Boring / Drilling : Rotary — Water Level : 23.90m b.g.l
Boring / Drilling Equipment : G.O.16 — Dia.of Boring / Drilling : Hx / Nx
Casing Lowered : Hx : 3.60m., Nx : 22.14m. — Date : From 23.06.11 To 28.07.11

Date (dd / mm)	Elevation (m)	Depth / RUN (m) From	To	Length (m)	Nature of Sampling	SPT 0-15 cm	15-30 cm	30-45 cm	45-60 cm	N' Value	Time Taken (min)	Total length of Core Pieces (m)	Core Recovery (%)	R.Q.D. (%)	Description
23/06	+179.3	0.00													
		0.50	-	-	D	-	-	-	-	-	-	-	-	-	Grey sand mixed with fragmented rock pieces
		1.00	1.45	0.45	P	5	7	9	-	16	-	-	-	-	-do-
		2.00	2.09	0.09	P	101 (9cm)	-	-	-	>100	-	-	-	-	-do-
		2.09	3.00	0.91	C	-	-	-	-	-	45	0.24	26	10	Highly weathered brownish - grey coloured medium grained flagy sandstone highly fractured, cores are broken into pieces
		3.00	3.75	0.75	C	-	-	-	-	-	35	0.12	16	Nil	-do-
		3.75	3.79	0.04	P	53 (4cm)	-	-	-	>100	-	-	-	-	
		3.79	4.50	0.71	C	-	-	-	-	-	54	0.41	58	54	Moderately weathered grey coloured, medium grained flagy sandstone, non - jointed
		4.50	5.25	0.75	-	-	-	-	-	-	50	Nil	Nil	Nil	Completely weathered product of rock
24/06		5.25	6.00	0.75	C	-	-	-	-	-	40	0.18	24	Nil	Highly weathered grey coloured medium grained flagy sandstone massive, fractured, cores are broken into pieces (fissile very intensely)

NOTES
1. Abbreviation Used : U-Undisturbed Sample C-Core Sample D-Disturbed Sample P-Standard Penetration Test V-Vane Shear Test
2. Level at which Artesian Condition experienced and its pressure, if any :
3. Water Loss with depth, if any :
4. Colour of water during drilling : Grey

Location : N 2978046 E 645002 — Ground Elevation : +160.1m
Method of Boring / Drilling : Rotary — Water Level : 6.55m b.g.l
Boring / Drilling Equipment : G.O.2 — Dia.of Boring / Drilling : Hx / Nx
Casing Lowered : Hx:2.36m., Nx:12.62m. — Date : From 20.07.11 To 05.08.11

Date (dd / mm)	Elevation (m)	Depth / RUN (m) From	To	Length (m)	Nature of Sampling	SPT 0-15 cm	15-30 cm	30-45 cm	45-60 cm	N' Value	Time Taken (min)	Total length of Core Pieces (m)	Core Recovery (%)	R.Q.D. (%)	Description
20/07	+160.1	0.00													
		0.50	-	-	D	-	-	-	-	-	-	-	-	-	Brownish yellow silty sand with fragmented rock pieces
		1.00	1.12	0.12	P	100 (12cm)	-	-	-	>100	-	-	-	-	Yellowish grey silty sand with fragmented rock pieces
21/07		1.12	2.00	0.88	C	-	-	-	-	-	65	0.26	30	Nil	Boulder upto depth 1.80m., rest of the core highly weathered light grey coloured fine to medium grained flagy sandstone, massive, highly fractured, fractured planes moderately rough and Fe-stained, cores are broken into pieces
		2.00	2.75	0.75	C	-	-	-	-	-	67	0.43	57	19	Moderately weathered light grey coloured fine to medium grained flagy sandstone, embedded with gravels, pebbles etc. massive, fractured at places
22/07		2.75	3.50	0.75	C	-	-	-	-	-	56	0.40	53	13	-do-
23/07		3.50	4.25	0.75	C	-	-	-	-	-	54	0.49	65	36	-do-
		4.25	5.00	0.75	C	-	-	-	-	-	52	0.49	65	17	-do-
25/07		5.00	5.75	0.75	C	-	-	-	-	-	50	0.45	60	23	-do-
		5.75	6.50	0.75	C	-	-	-	-	-	54	0.44	59	39	-do-

NOTES
1. Abbreviation Used : U-Undisturbed Sample C-Core Sample D-Disturbed Sample P-Standard Penetration Test V-Vane Shear Test
2. Level at which Artesian Condition experienced and its pressure, if any :
3. Water Loss with depth, if any :
4. Colour of water during drilling : Grey

Organisation: IRCON — Co-ordinates : N 2987020.7, E 641681.7 — Drill Hole No: AP-3
Project: Sevok - Rangpo New BG Rail line. — Ground Elevation : +294.1m — Type of core barrel : Double Tube
Location : T-6 Adit Portal A-1, 10m left — Total Length : 15.85m — Angle with Horizontal : 90°
Drilling Agency : Constell Consultants Pvt. Ltd. — Started : 28.10.13 — Completed : 11.11.13

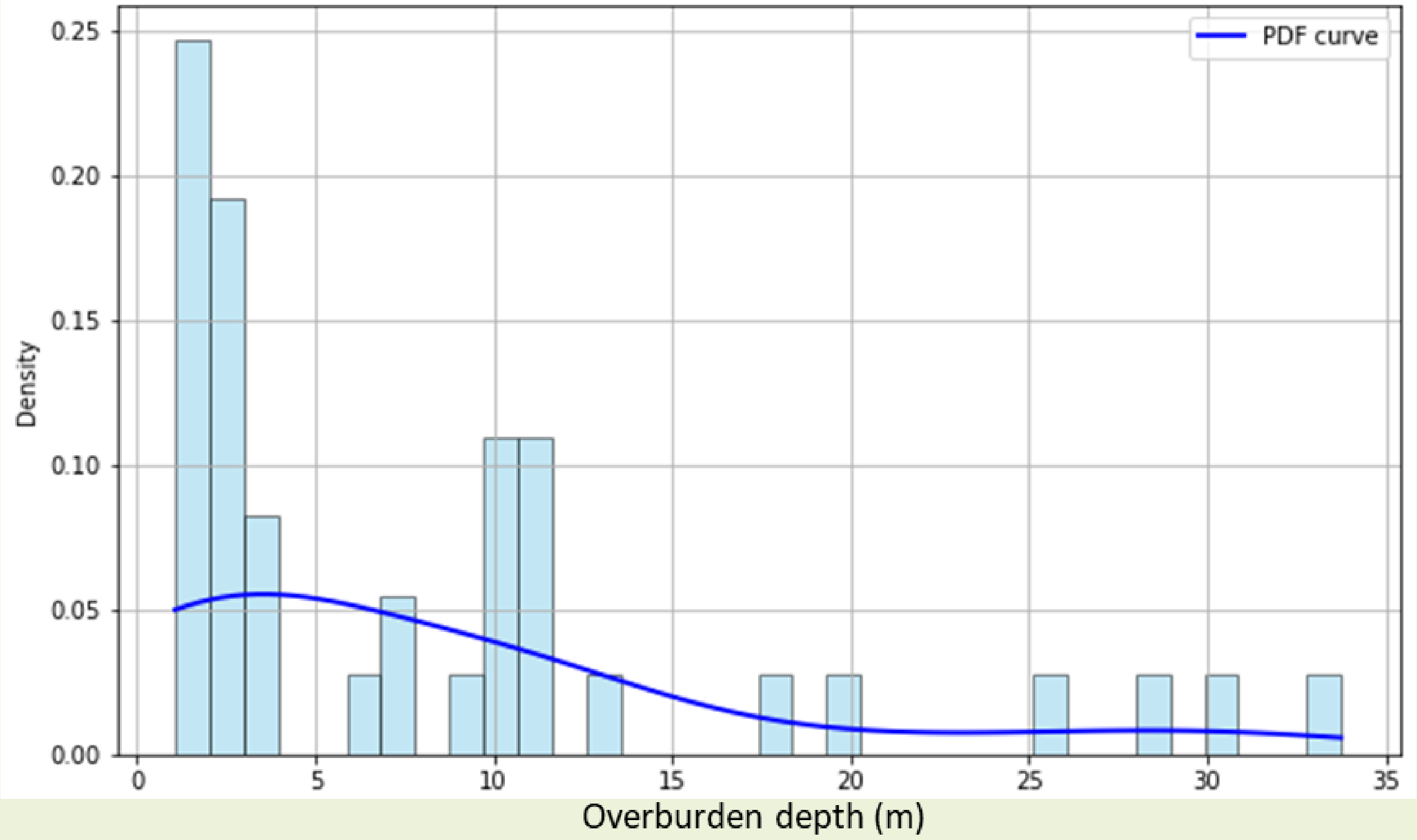
Elevation, (m)	Length (m)	Lithology Description	Percent Core Recovery	R.Q.D (%)	Depth of Water Level	Penetration Rate (mm / min)	Special Observation and Interpretation
+294.1	0.00	Dark grey silty sand with fragmented rock pieces					SPT 0.70m-0.75m N=>100 (56 blows for 5cm) Bed Rock Starts from 1.00m depth.
+293.4	0.75	Completely weathered product of rock				16.66	
+293.1	1.00	Highly weathered greyish green coloured fine to medium grained chlorite schist.	13	Nil		16.66	Highly fractured , cores are broken into pieces.
+292.4	1.75	Completely weathered product of rock				25.00	
+291.6	2.50	Highly weathered greyish green coloured fine to medium grained chlorite schist.	12	Nil	NOT ENCOUNTERED	18.75	Highly fractured , cores are broken into pieces.
	3.25		21	Nil		16.66	
	4.00		16	Nil		15.00	
	4.75		23	Nil		8.82	
	5.50		24	Nil		8.33	
+287.9	6.25	Highly weathered dirty grey coloured fine grained quartzite	45	Nil		9.37	Highly fractured
	7.00		40	Nil		5.55	

Logged by A. K. Banerjee — Approved by B. N. Basak — Checked by S. Bhattacharjee

Geotechnical Investigations: Overburden Depth

From 124 borehole data

- Mean: 8.5 m
- Standard Deviation: 8.9 m
- Q1 (25th percentile): 2.2 m
- Q2 (Median, 50th percentile): 3.5 m
- Q3 (75th percentile): 11 m
- 90th percentile: 22.3 m

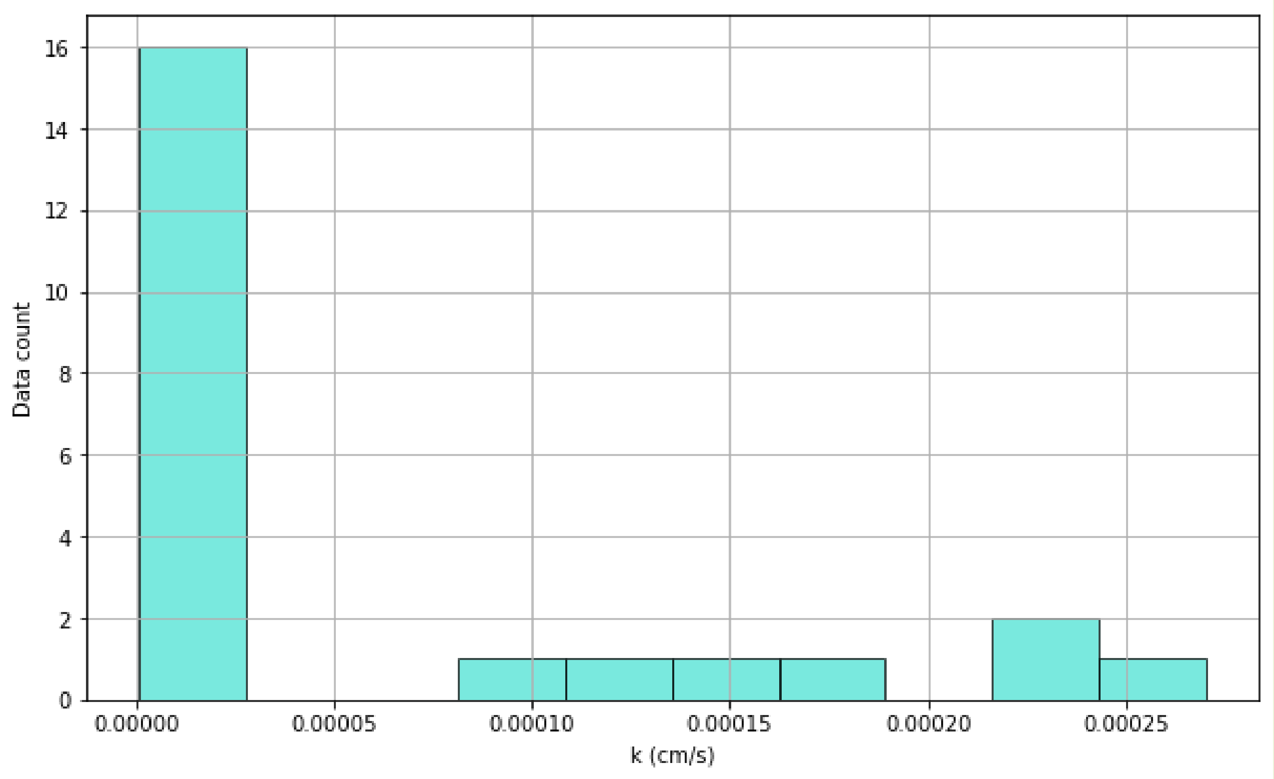


Histogram and PDF curve for the overburden depth

Geotechnical Investigations: Overburden Depth

From 23 field permeability test data

- Mean: 5.94 10^{-5} m/s
- Standard Deviation: 8.93×10^{-6} m/s
- Q1 (25th percentile): 2.23×10^{-6} m/s
- Q2 (Median, 50th percentile): 6.93×10^{-6} m/s
- Q3 (75th percentile): 1.1×10^{-4} m/s



Histogram of the k-values for the soil layer

Geotechnical Investigations: Density and Shear Strength

- **Density from 97 borehole data**
  - Saturated density was calculated from water content data
  - No major variation

Parameters	Bulk density (g/cc)	Dry density (g/cc)	Sat. density (g/cc)
Avg	1.91	1.62	2.02
SD	0.05	0.06	0.04
CV	0.03	0.04	0.02

Parameter	Cohesion (kg/cm^2)	ϕ (°)
Avg	0.06	32.72
SD	0.06	1.61
CV	1.07	0.05

- **Shear strength parameters from 57 soil testing data**
  - Mostly cohesionless soil
  - No major variation

Geotechnical Investigations: Unsaturated Strength Parameters

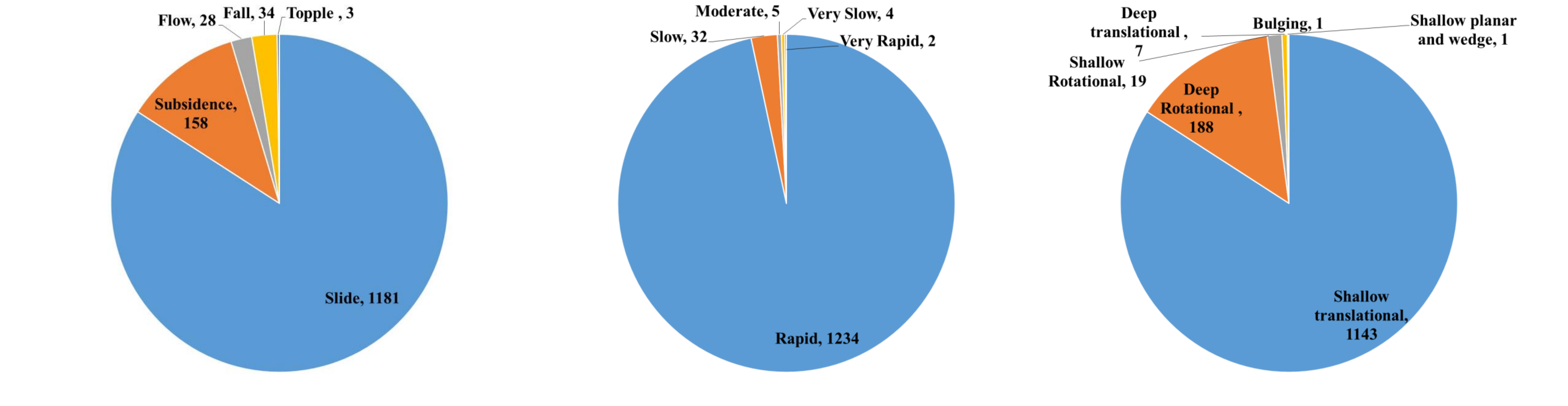
Statistical parameters of the van Genuchten parameters determined by Rosetta method

Parameters	α	n	θ_r	θ_s
Mean	0.020	1.729	0.05	0.34
SD	0.008	0.422	0.007	0.005
Median	0.019	1.556	0.047	0.337
CV	0.398	0.244	0.143	0.014

Summary of Geotechnical Parameters for Numerical Modeling

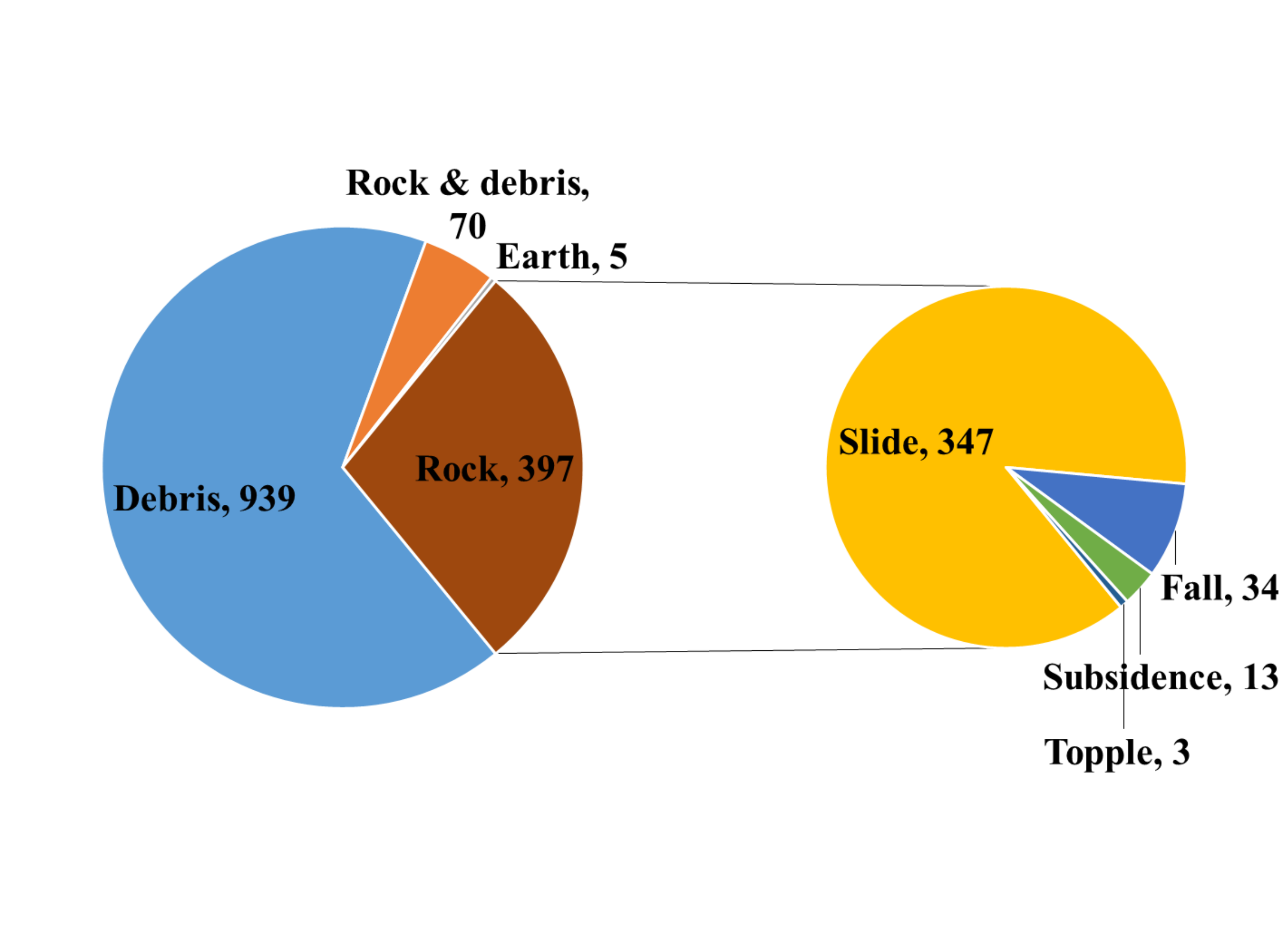
Properties	Soil (Mean values)	Bedrock (Mean values)
a. Overburden depth (m)	3.5, 11, 22.3	-
b. Modulus of elasticity (kPa)	-	5.0754×10^6
c. Bulk density (g/cc)	1.91	2.69
d. Dry density (g/cc)	1.62	-
e. c (kN/m^2)	6	1700
f. ϕ (°)	32.72	41
g. van Genuchten parameters		
• α	0.02	
• n	1.729	-
• θ_r	0.05	
• θ_s	0.34	
h. k (cm/s)	6.93×10^{-4}	2.88×10^{-4}

Landslide Attribute Analysis from Available Landslide Records

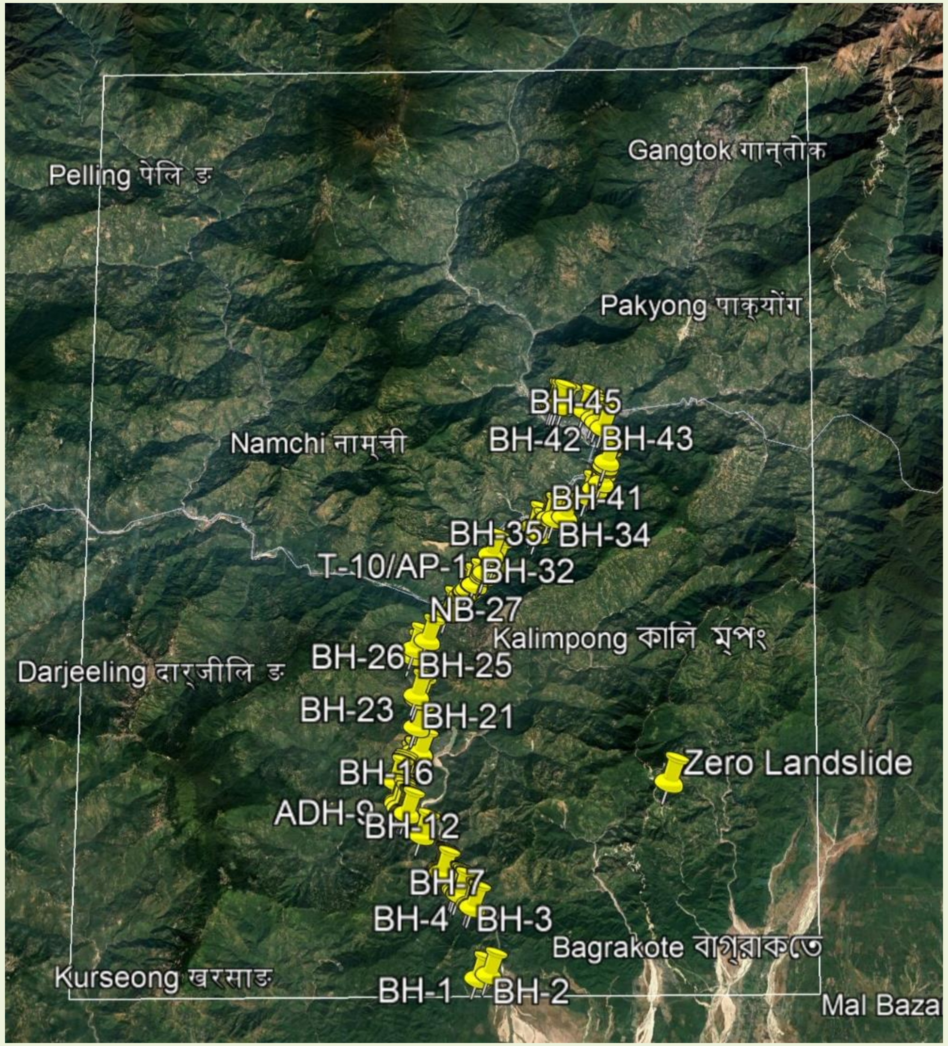


Movement type | Movement rate | Failure Mechanism

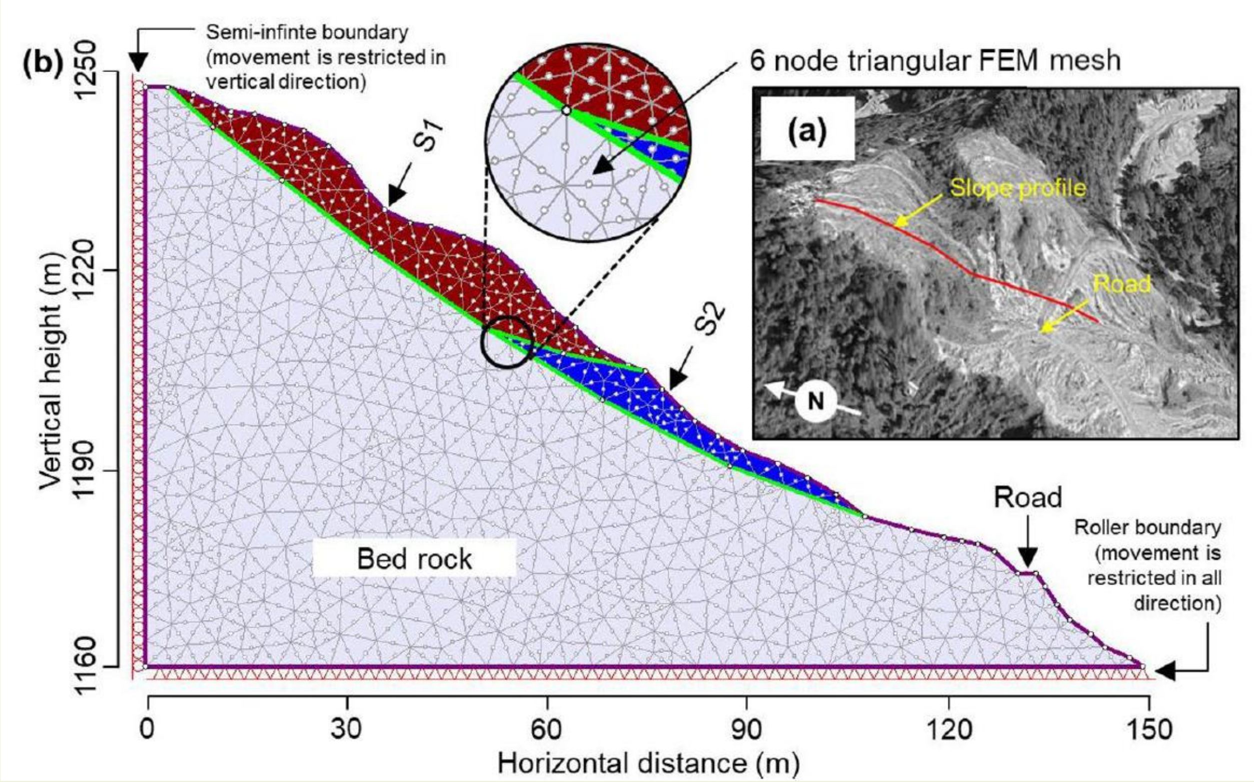
Landslide Attribute Analysis from Available Landslide Records



Validation Study: Zero Landslide

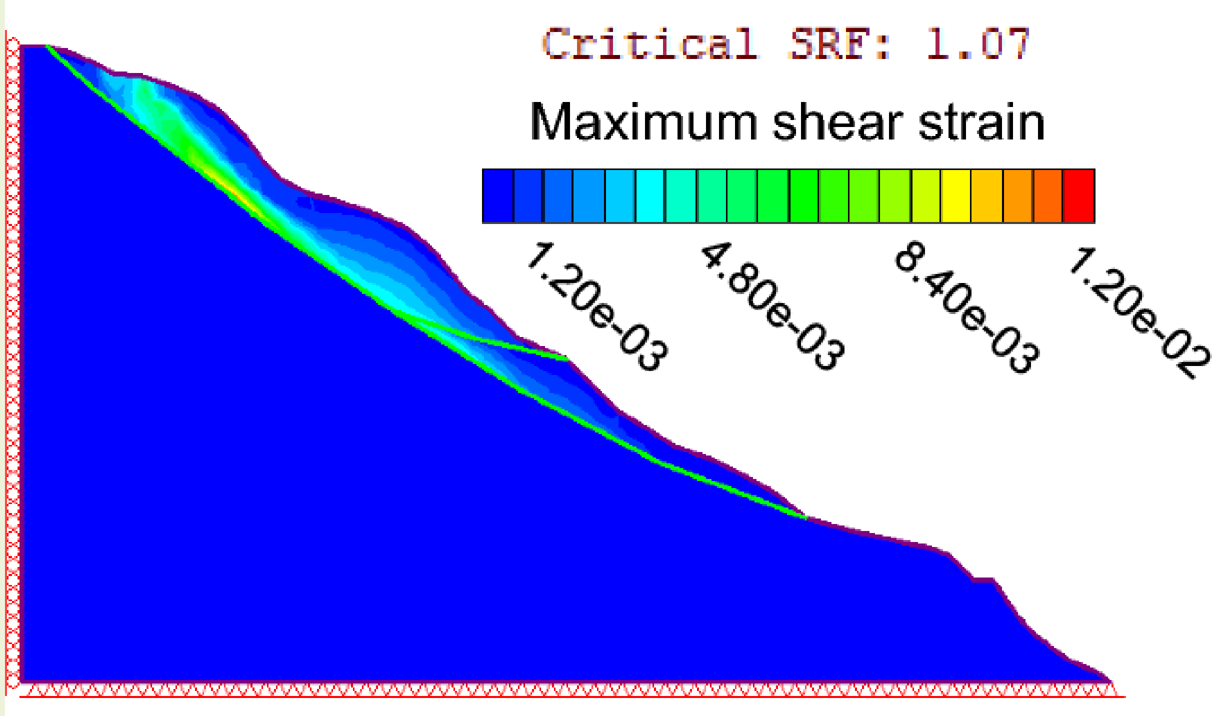


Google Earth image of the study area depicting the borehole locations and Zero landslide

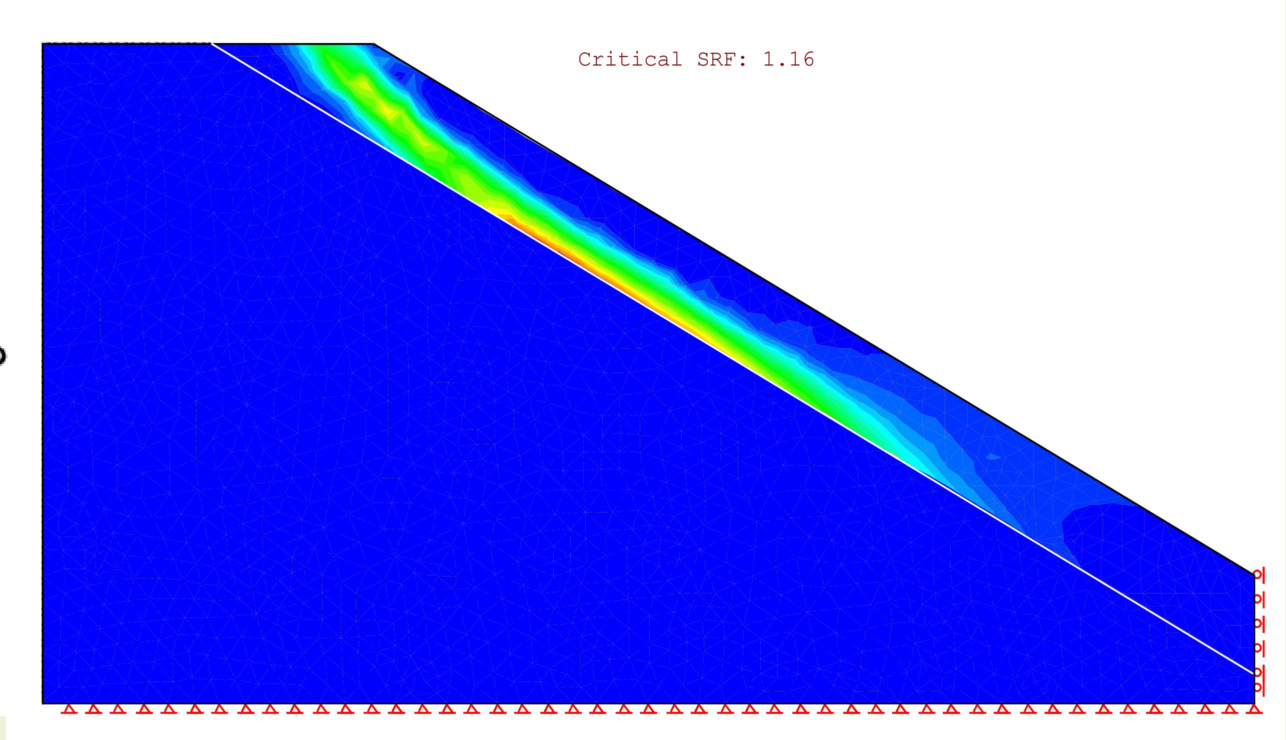


Slope profile adopted in the stability assessment by Das et al. (2024)

Validation Study: Zero Landslide



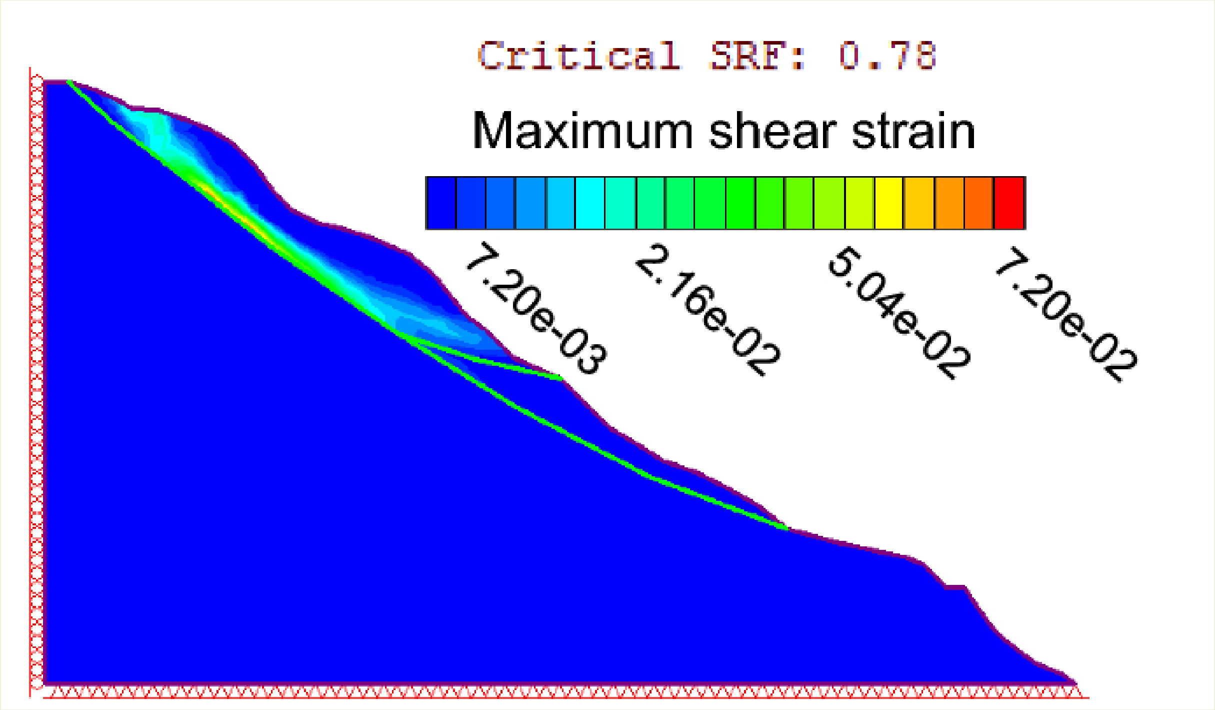
(a)



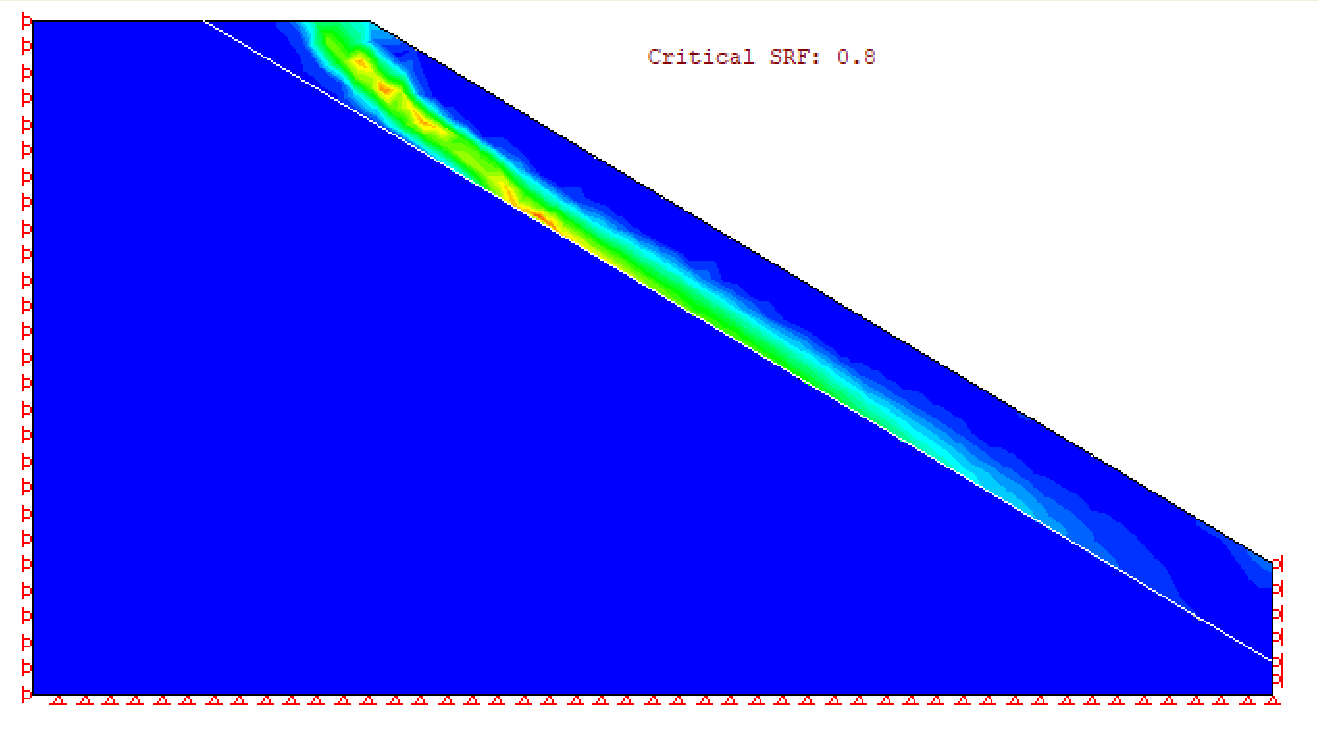
(b)

Maximum shear strain contour – dry condition (a) Das et al., 2024 (b) Current study

Validation Study: Zero Landslide



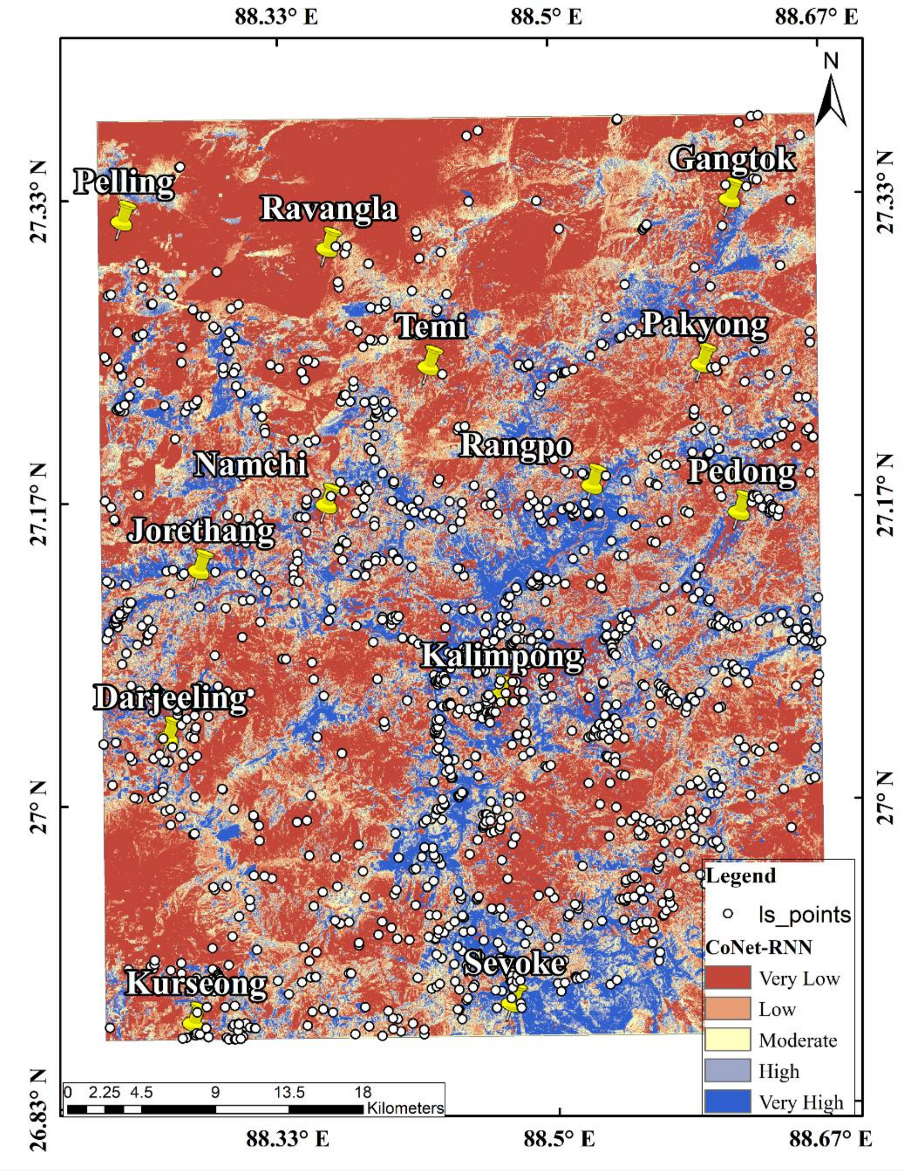
(a)

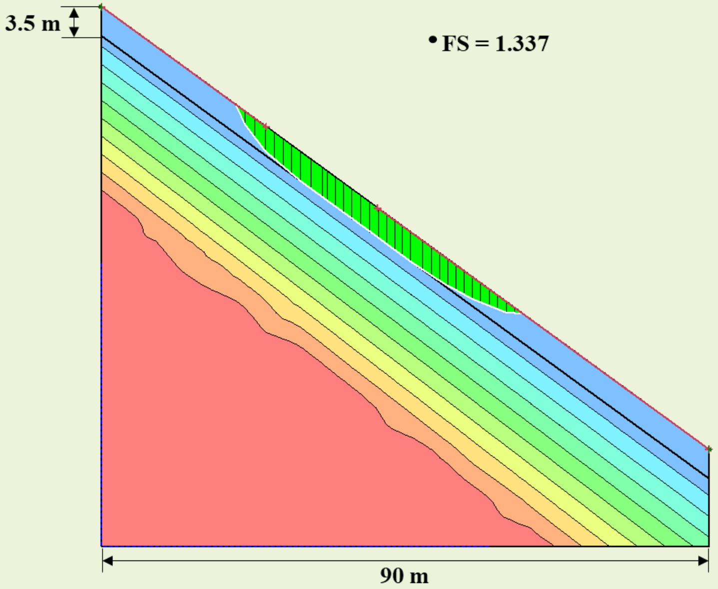


(b)

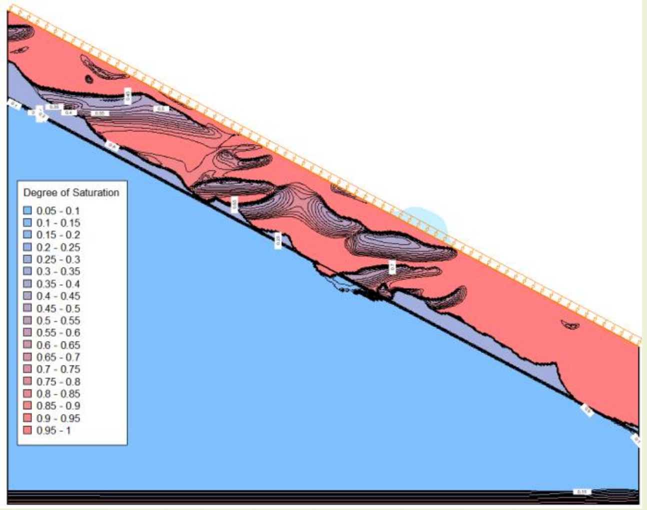
Maximum shear strain contour – wet condition (a) Das et al., 2024 (b) Current study

Modified LSM of Sikkim: Improvisations in Subsurface Saturation

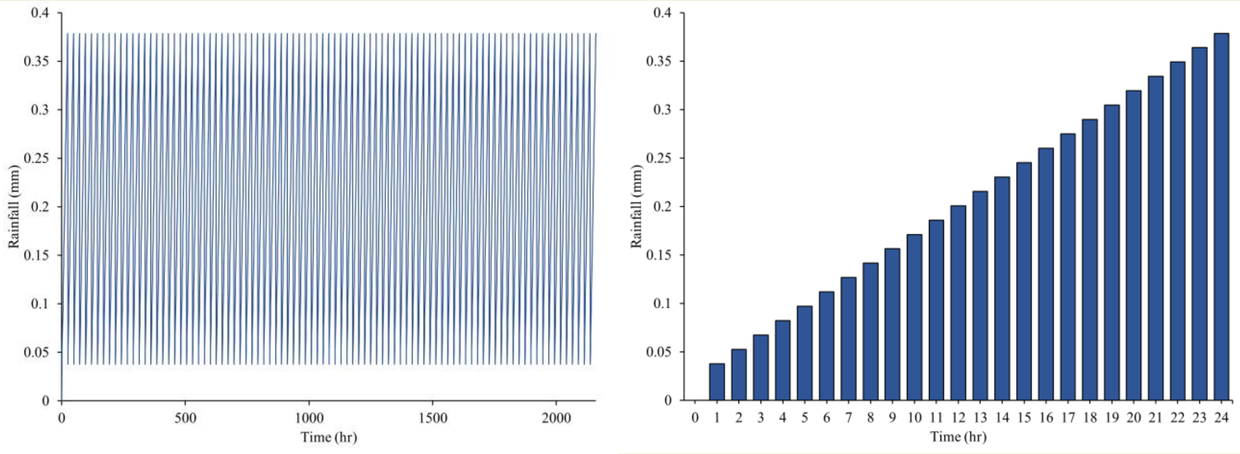




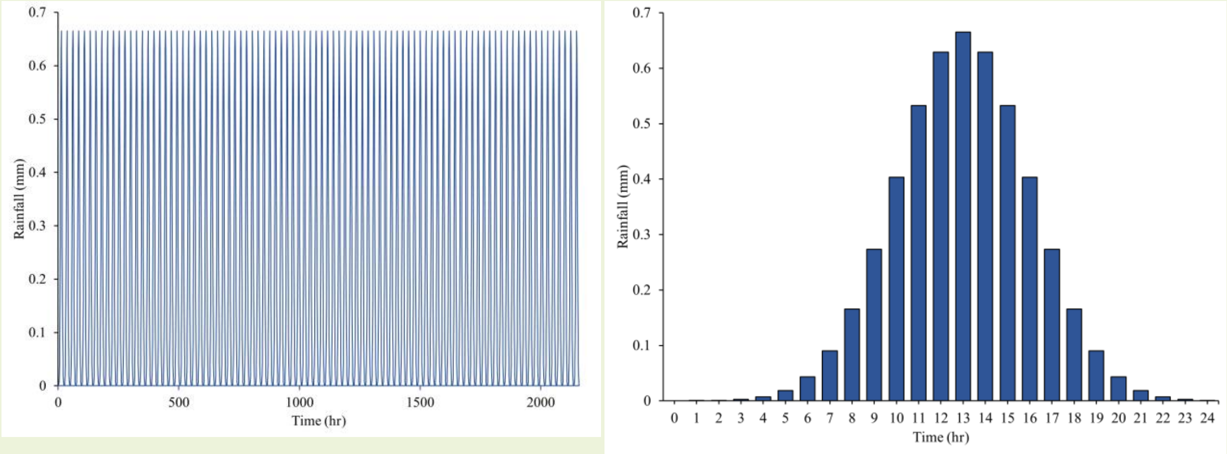
Development of Surrogate Models



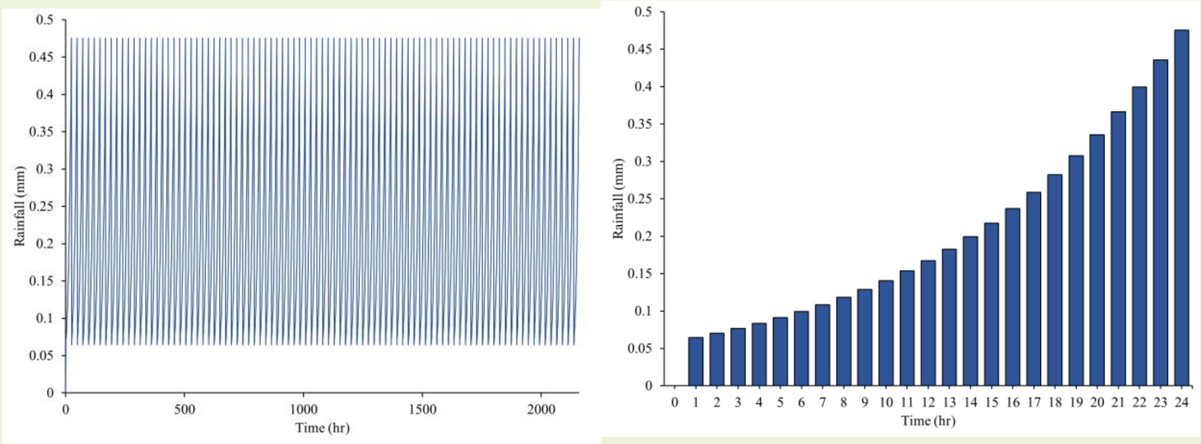
Modified LSM of Sikkim: Improvisations in Rainfall Reealizations



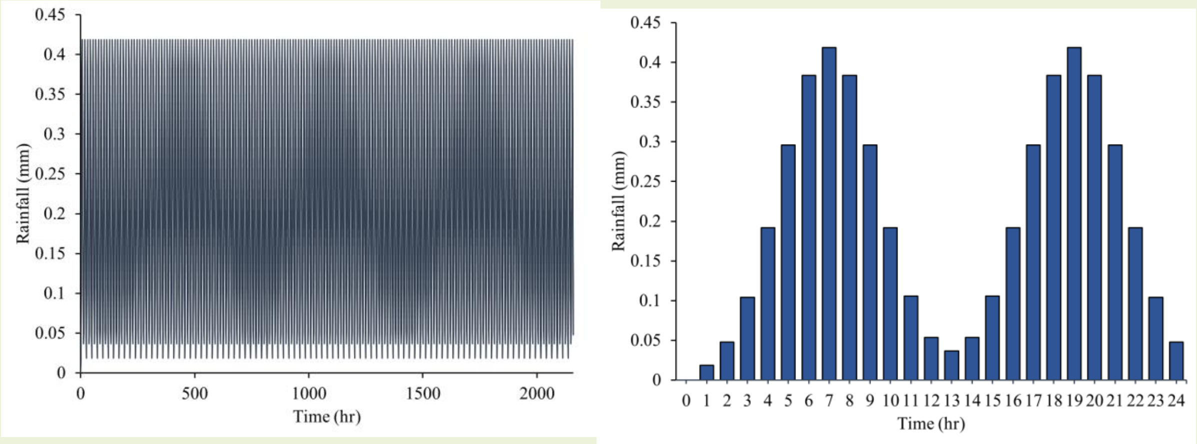
RFR2 - Linearly increasing



RFR3- Normally distributed



RFR4 - Exponentially increasing



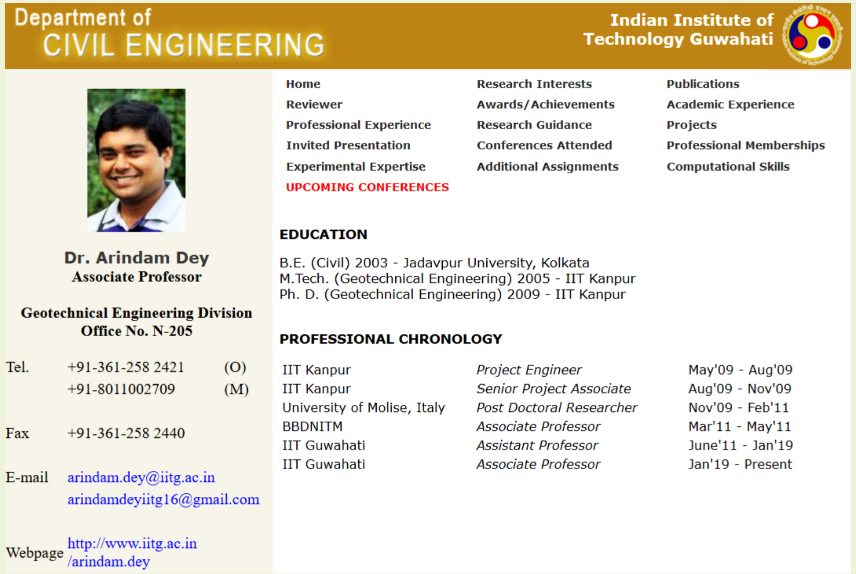
RFR5 - Bi-modal

Future Pathways

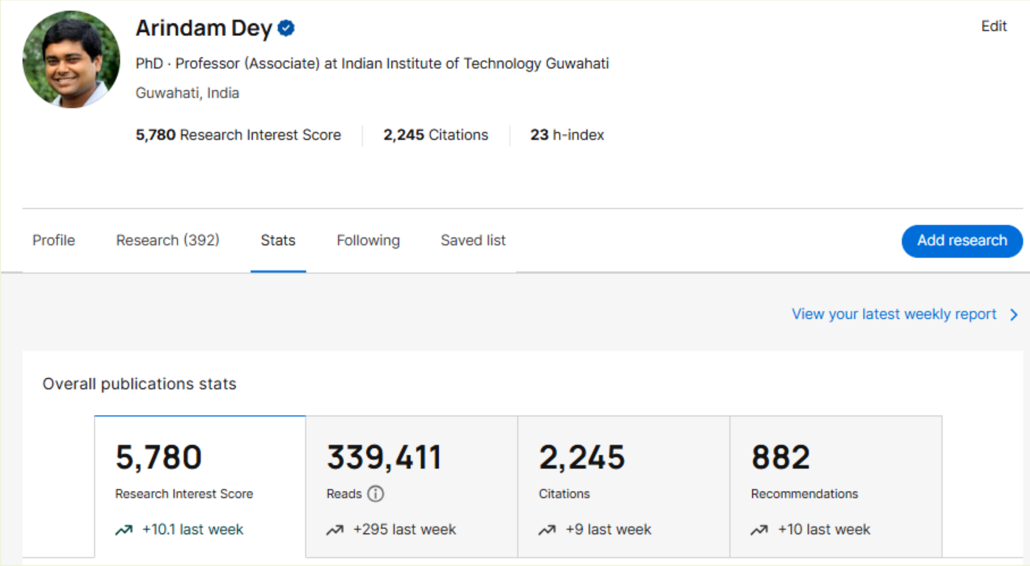
- **Visions to strengthen such exercises in future for various regions**
  - ❖ Focus on strengthening landslide inventory
  - ❖ More trials with high-resolution dataset
  - ❖ Updated land use and land cover information owing to progressive urbanization
  - ❖ Updated landslide conditioning factor dataset
  - ❖ Consideration of changing rainfall dynamics
  - ❖ Efforts to be given to develop standardized approach

Further Interaction and Information

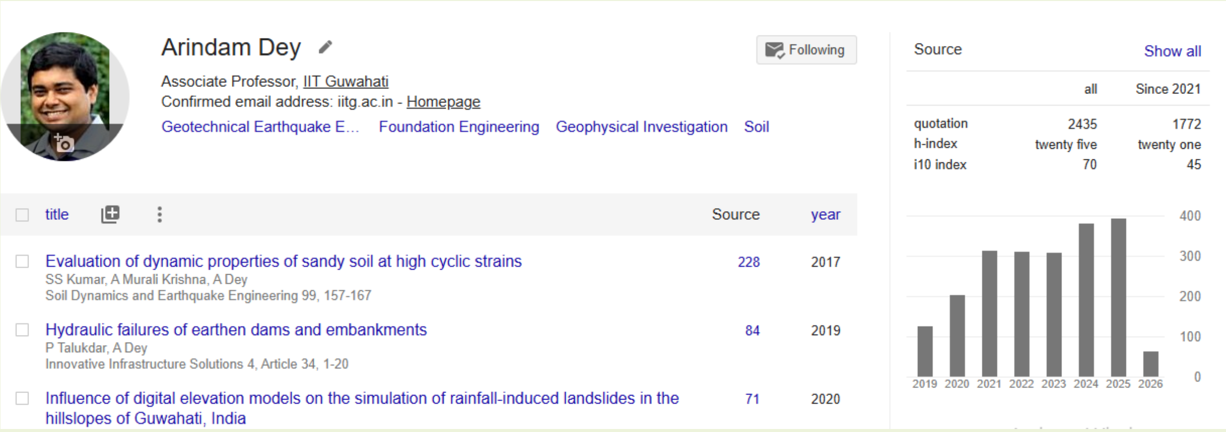
Webpage



- Researchgate



- Google Scholar



Some Glimpses of the IIT Guwahati Campus

Thank You for Patient Hearing

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