GEOLOGICAL SURVEY OF INDIA

Landslide Hazard & Risk Analysis

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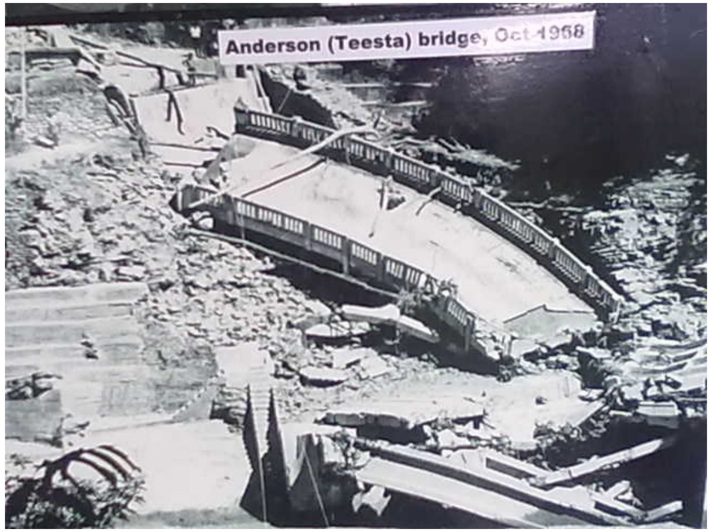
We will discuss…

- **Definitions** & Landslide Risk Management Framework
- Landslide **Susceptibility** Analysis (LSA): **Macro** scale **1:50,000**
  - Why – Empirical Techniques ???
  - Empirical LSA – Conceptual Model
  - Empirical LSA – Processes and Steps
- **Debris flow impact probability**
- **Landslide Management Map**
- Landslide **Hazard** & **Risk** Analysis
  - Data Requirement and Methodology
  - Limitations and Constraints

Landslide – A complex hazard



Profuse loss of resources

Varied magnitudes … varied extent of effects … **A HAZARD!!!**

Definition of Landslide Risk

- Risk is the amalgam of the **likelihood and amount of potential adverse consequences to an element at risk** arising from a landslide event of certain magnitude within a stated period and area.

- Lee and Jones, 2004

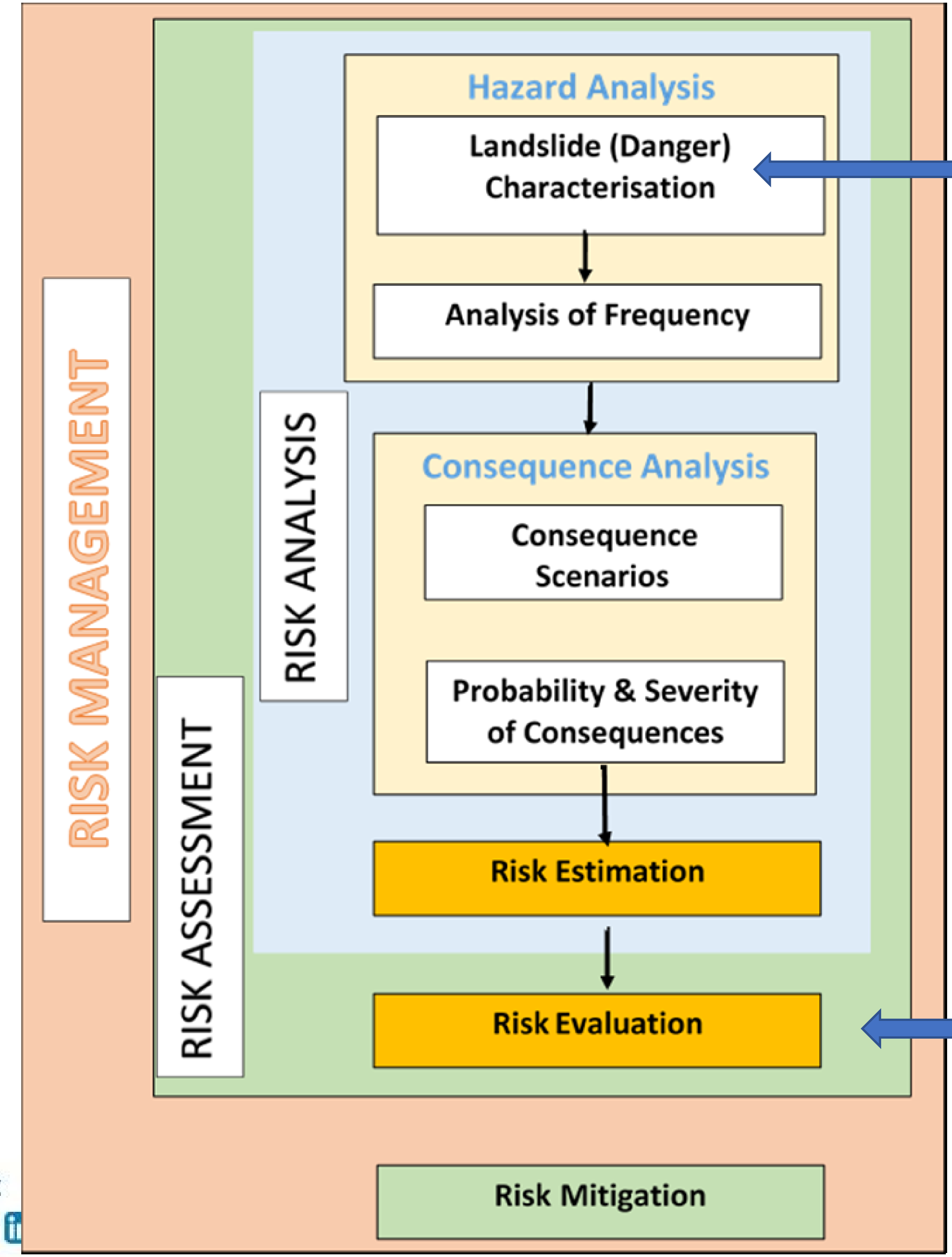
Definition of Landslide Hazards

- According to Varnes (1984) & UNESCO's IAEG Commission on landslides and other mass movements and Guzzetti (1999), "landslide hazard" is defined as the **probability of occurrence of a damaging landslide of a certain magnitude in a given area and in a given period of time.**
- Therefore, landslide hazard in a given area is a function of three parameters, namely, **spatial**, **temporal** and **magnitude** probabilities of landslide occurrence.

Landslide Hazards Analysis

- Spatial Prediction: Where will a landslide occur ???
- Temporal Prediction: When will it occur ???
- Magnitude Prediction: How large or how big that landslide/ the landslide event could be ???

Landslide Susceptibility Analysis (LSA) is the method to predict the spatial locations where the future landslides can occur



Landslide Susceptibility Analysis (LSA)

Landslide Risk Management Framework

Making judgments "on the tolerability of the risk on the basis of a risk analysis" while considering influencing factors

Fell *et al.*, 2005

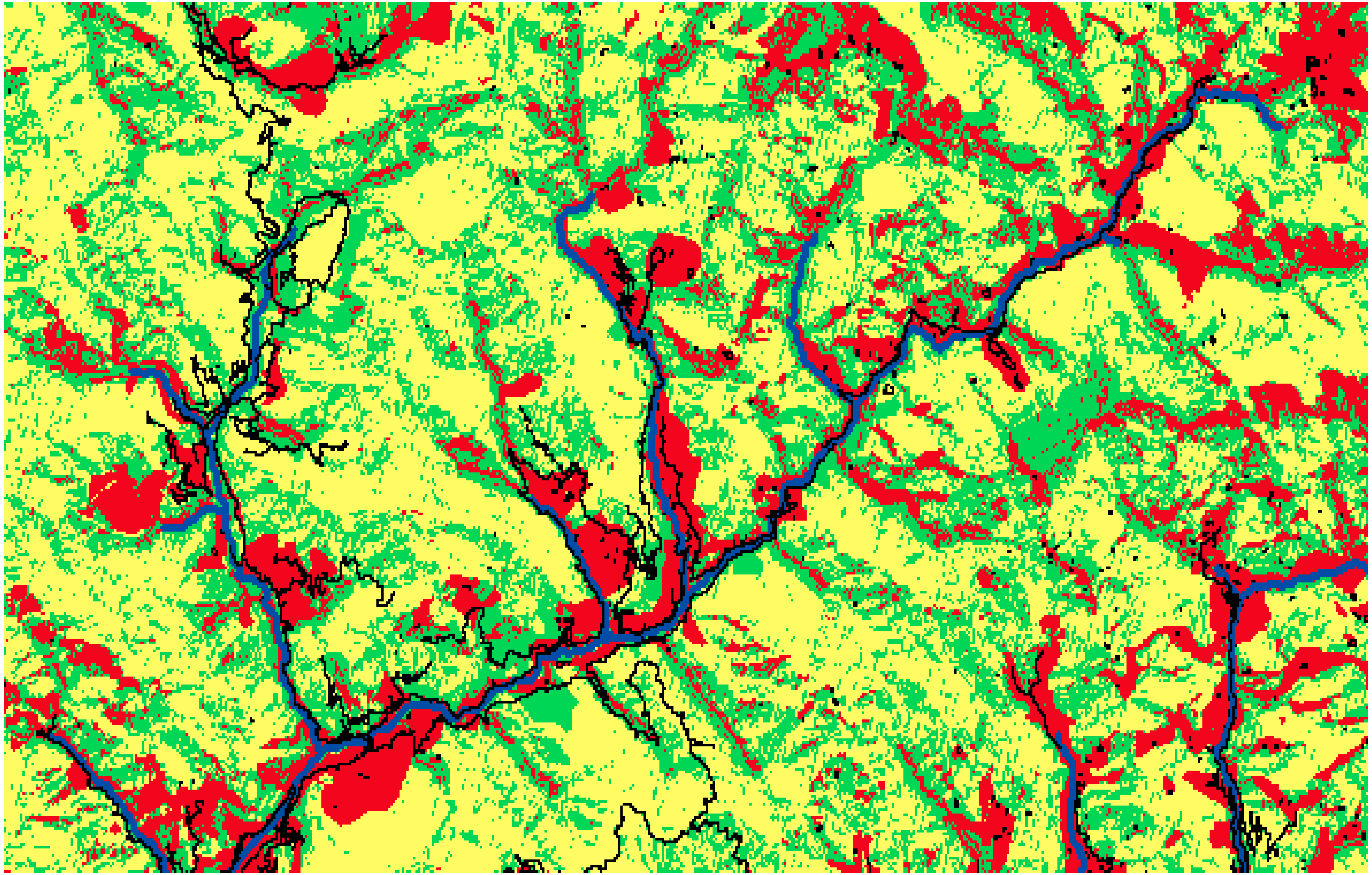
Landslide Zoning – A multi-scale & multi-purpose exercise

Purpose		Type of Zoning				Levels of Zoning			Mapping Scale
		Inventory	Susceptibility	Hazard	Risk	Primary	Intermediate	Advanced	
Regional Zoning	Information	Green	Green	White	White	Green	White	White	1:50,000 and smaller
	Advisory	Green	Green	Yellow	Yellow	Green	Yellow	White	
	Statutory	Red	Red	White	White	White	White	White	
Local Zoning	Information	Green	Green	Green	Yellow	Green	Yellow	White	1:5000 to 1:10,000
	Advisory	Yellow	Green	Green	Green	Green	Green	Green	
	Statutory	White	Yellow	Green	Yellow	White	Green	Green	
Site-specific Zoning	Information	Red	White	White	White	White	White	White	1:5000 or larger
	Advisory	White	Yellow	White	White	White	White	White	
	Statutory	White	Yellow	Green	Green	White	Green	Green	
	Design	White	Yellow	Yellow	Green	White	Yellow	Green	

Green	Applicable
Yellow	May be applicable
Red	Not Recommended
White	May not be feasible

- **Purpose**
- **Type**
- **Level**
- **Scale**

Understanding Landslide Susceptibility



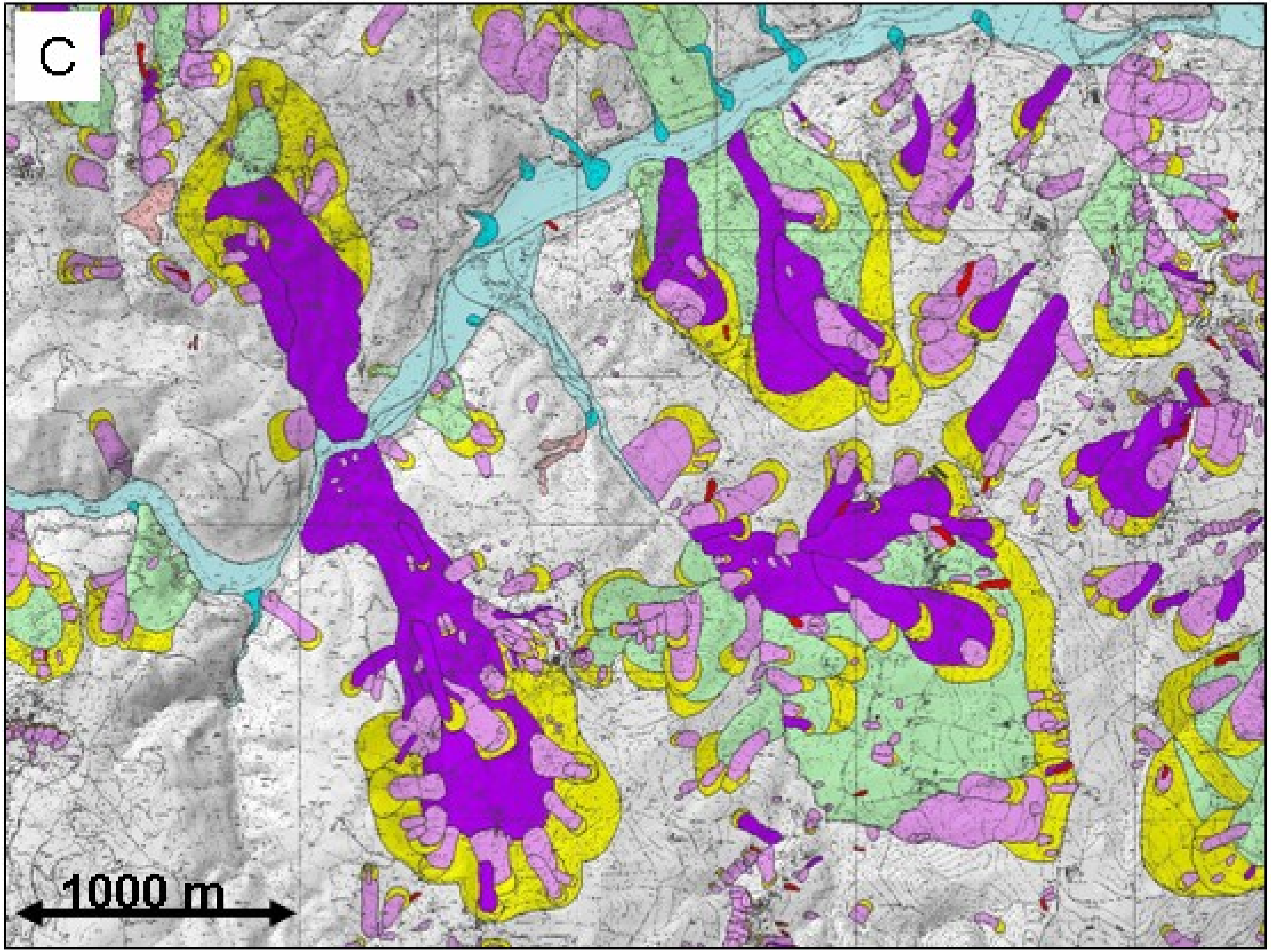
Red – High; Green – Moderate & Yellow – Low;

Methodology: LSA (Macro scale 1:50,000)

- Using heuristic (knowledge-driven) approach, where a-priori knowledge on landslides is insufficient or absent (Direct and Indirect/ semi-quantitative)

- Or, through various data-driven empirical (statistical) techniques using the a-priori knowledge on past/present landslides

Heuristic/ Knowledge Driven (Direct)



Geomorphic mapping

Understanding Processes as well as Landforms

Heuristic/ Knowledge Driven (Direct)

Limitations & Constraints

✓Depends on the expertise and experience levels of the geoscientists engaged in geomorphic mapping.

✓Time consuming and costly exercise

✓Scope of validation in general is absent or not followed.

Heuristic/ Knowledge Driven (Indirect)

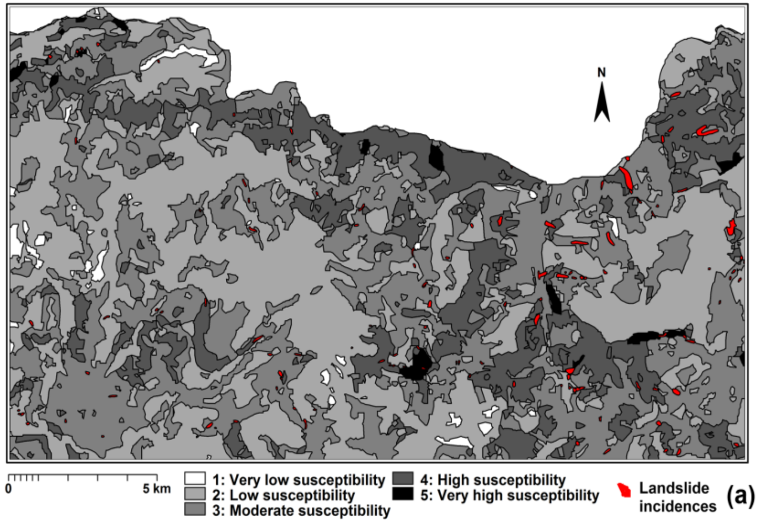
✓It is based on specified weights or ranks to a set of pre-defined spatial factors (e.g. BIS method 1998)

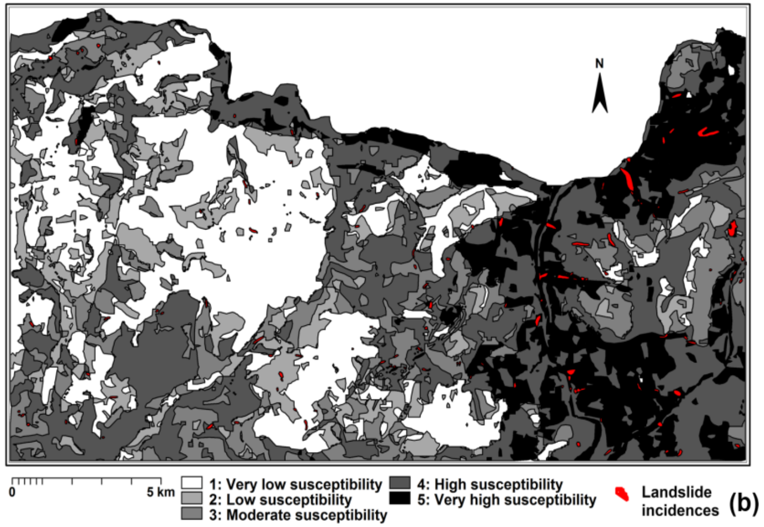
✓Which is an Indirect knowledge-driven (heuristic) method originally proposed by Anbalagan (1992).

Heuristic/ Knowledge Driven (Indirect)

Geofactor	Description		Category	LHEF
Lithology	Rock type	Type 1	Quartzite & Limestone	0.2
	Type – 1**		Granite & Gabbro	0.3
	Highly weathered (4);		Gneiss	0.4
	moderately weathered (3);	Type 2	Sandstone & minor beds of claystone	1.0
	Slightly weathered (2)		Poorly cemented sandstone with minor clay/shale	1.3
	Type – 2 **		Slate & phyllite	1.2
	Highly weathered (4);	Type 3	Schist	1.3
	Moderately weathered (3);		Shale with interbedded clayey & non-clayey	1.8
	Slightly weathered (2)		Highly weathered shale, phyllite & schist	2.0
	Soil type		Older well compacted alluvial fill material	0.8
			Clayey soil with naturally formed surface	1.0
			Sandy soil with naturally formed surface (alluvial)	1.4
			Debris comprising mostly rock pieces mixed with clayey/ sandy soil (colluvial) – older well compacted	1.2
			Debris comprising mostly rock pieces mixed with clayey/ sandy soil (colluvial) – younger loose material	2.0
Structure	Relationship of parallelism between the slope and vulnerable discontinuity		> 30°	0.20
			21° – 30°	0.25
			11° – 20°	0.30
			6° – 10°	0.40
			< 5°	0.50
	Relationship of dip of vulnerable discontinuity and inclination of slope		> 10°	0.3
			0° – 10°	0.5
			0°	0.7
			0° – (-10°)	0.8
			< -10°	1.0
	Dip of vulnerable discontinuity		< 15	0.20
			16° – 25°	0.25
			26° – 35°	0.30
			36° – 45°	0.40
			> 45°	0.50
	Depth of soil cover		< 5m.	0.65
			6 – 10m.	0.85
			11 – 15m.	1.30
			16 – 20m.	2.0
Slope	Escarpment / cliff		> 45°	2.0
	Steep slope		36° – 45°	1.7
	Moderately steep slope		26° – 35°	1.2
	Gentle slope		16° – 25°	0.8
	Very gentle slope		< = 15°	0.5
Relative relief	< 100m.			0.3
	101 – 300m.			0.6
	> 300m.			1.0
Landuse and land cover	Agricultural land / populated flat land			0.60
	Thickly vegetated forest area			0.80
	Moderately vegetated area			1.20
	Sparsely vegetated area with less ground cover			1.50
	Barren land			2.0
Hydro-geological conditions	Flowing			1.0
	Dripping			0.8
	Wet			0.5
	Damp			0.2
	Dry			0.0

TEHD Values	Landslide susceptible zone (LHZ) Class	Category
< 3.5	1	Very Low Susceptibility
3.5 – 5.0	2	Low Susceptibility
5.0 – 6.0	3	Moderate Susceptibility
6.0 – 7.5	4	High Susceptibility
> 7.5	5	Very High Susceptibility

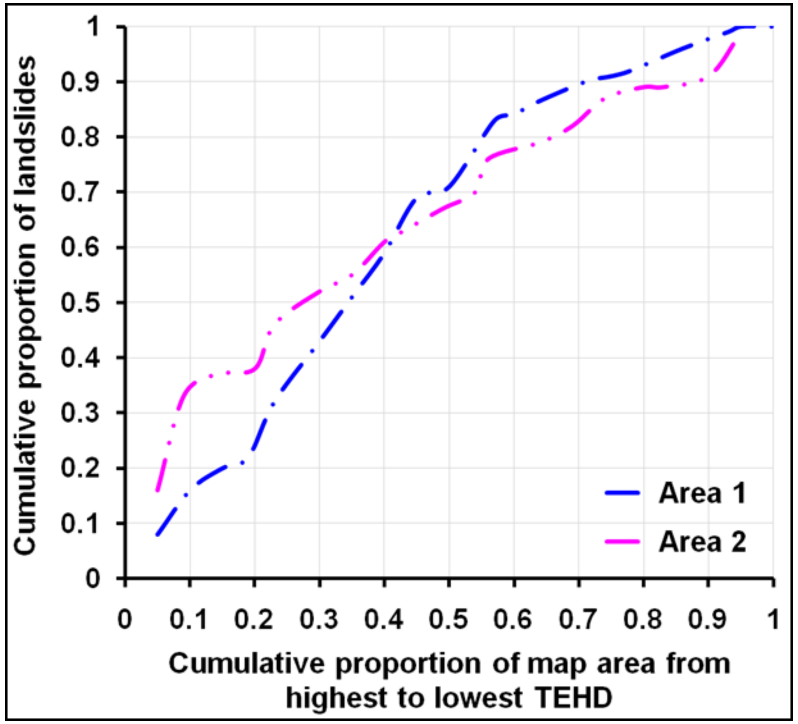


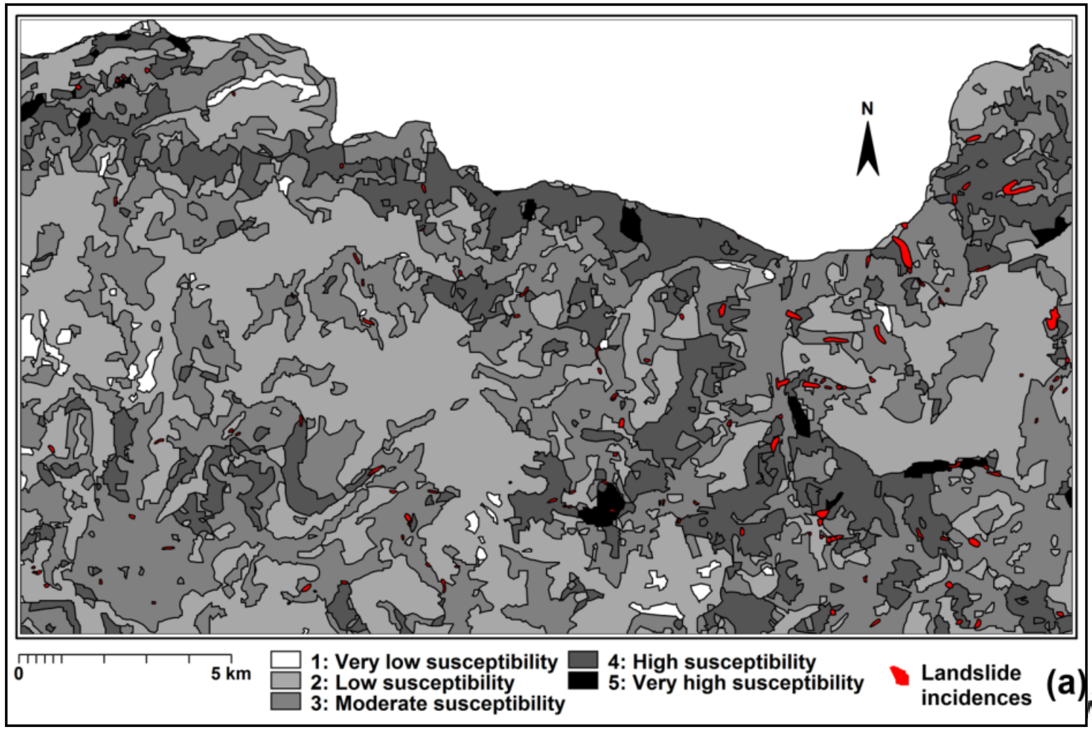


Heuristic/ Knowledge Driven (Indirect)

Limitations & Constraints

- Pre-defined factors & weights may lead to poor prediction
- Specific knowledge on landslide types & processes is not used
- No proper methods of validation suggested





Data-driven Empirical Method

- These methods are mainly based on various statistical and/or mathematical techniques using the a-priori knowledge on past/present landslides

    - Bivariate statistics
    - Multivariate statistics (DFA, LR)
    - Artificial Neural Network (ANN)
    - Bayesian Belief Function … etc.

Data-driven Empirical Method

Bivariate process

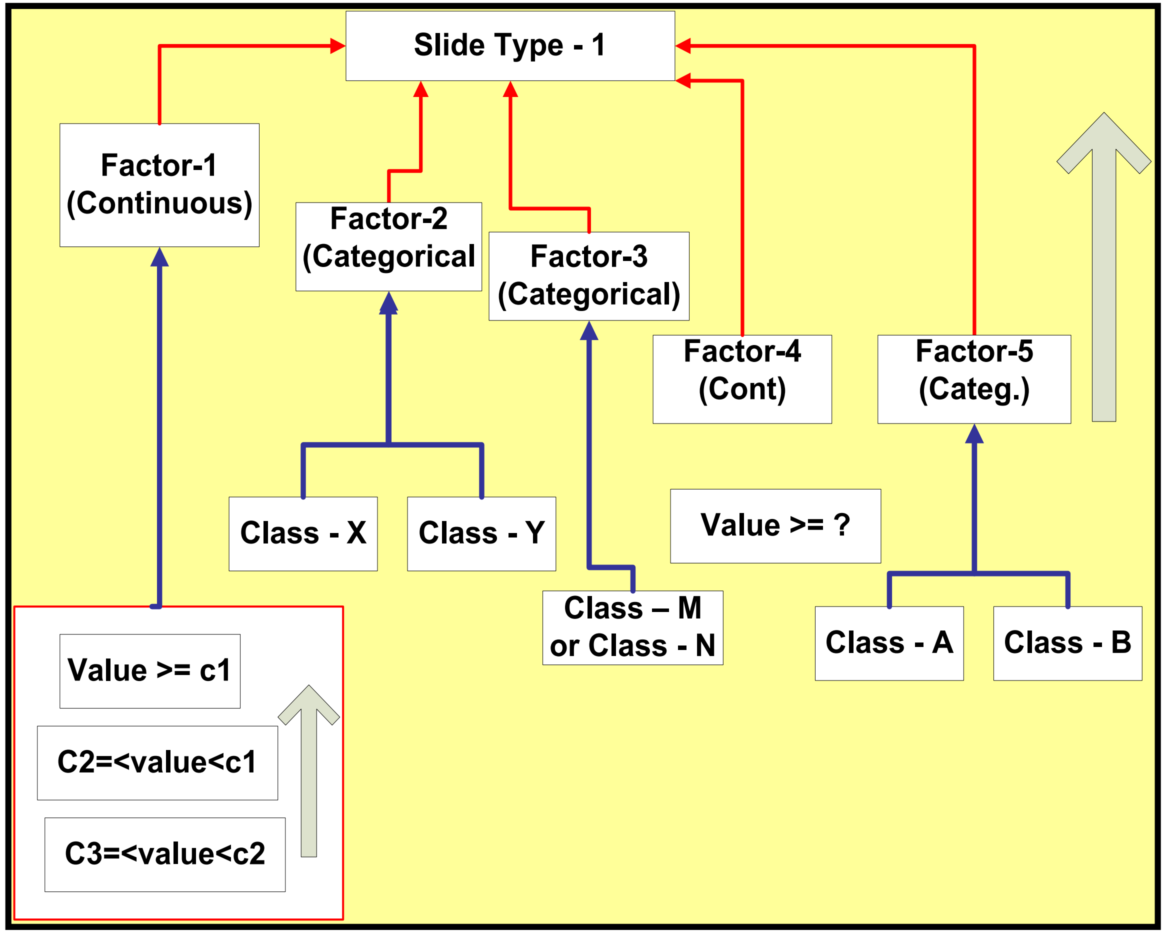
- Intuitive and instructive.
- Intervention by experts…possible
- Easy to use and understand the model processes.

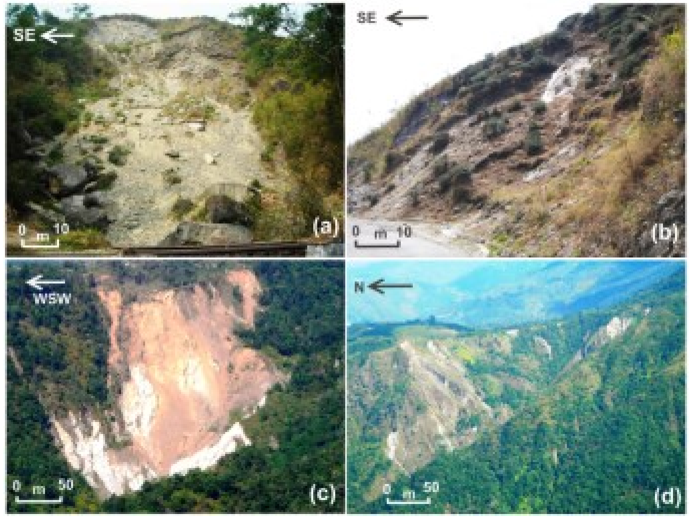
Multivariate process or ANN

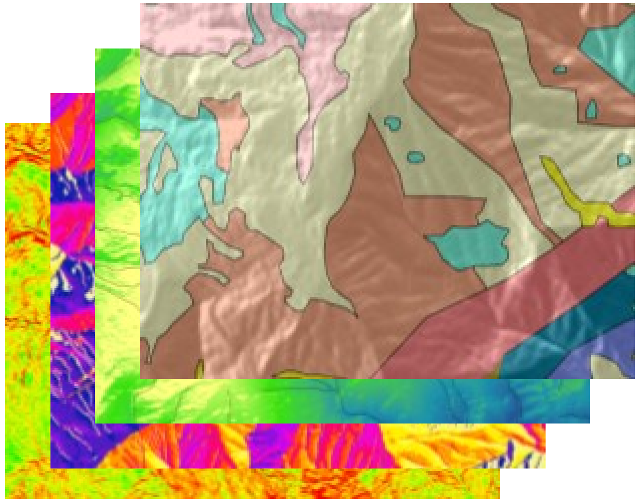
- Mostly black box type; difficult to understand model processes.
- Scope of intervention by experts is limited to none.
- Sometimes select the predictors having least genetic implications.

Data-driven Empirical - Methodology

Conceptual Model







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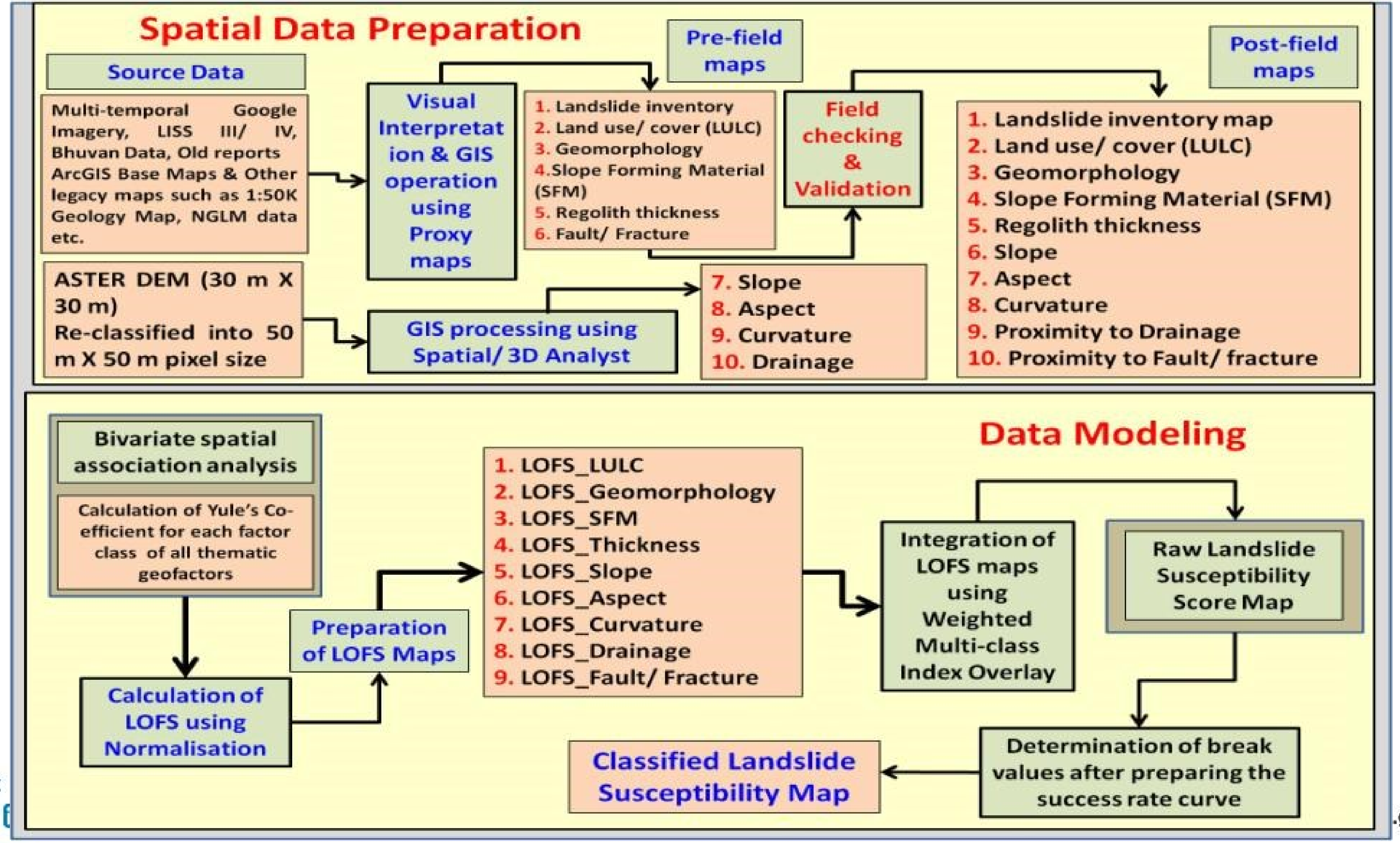
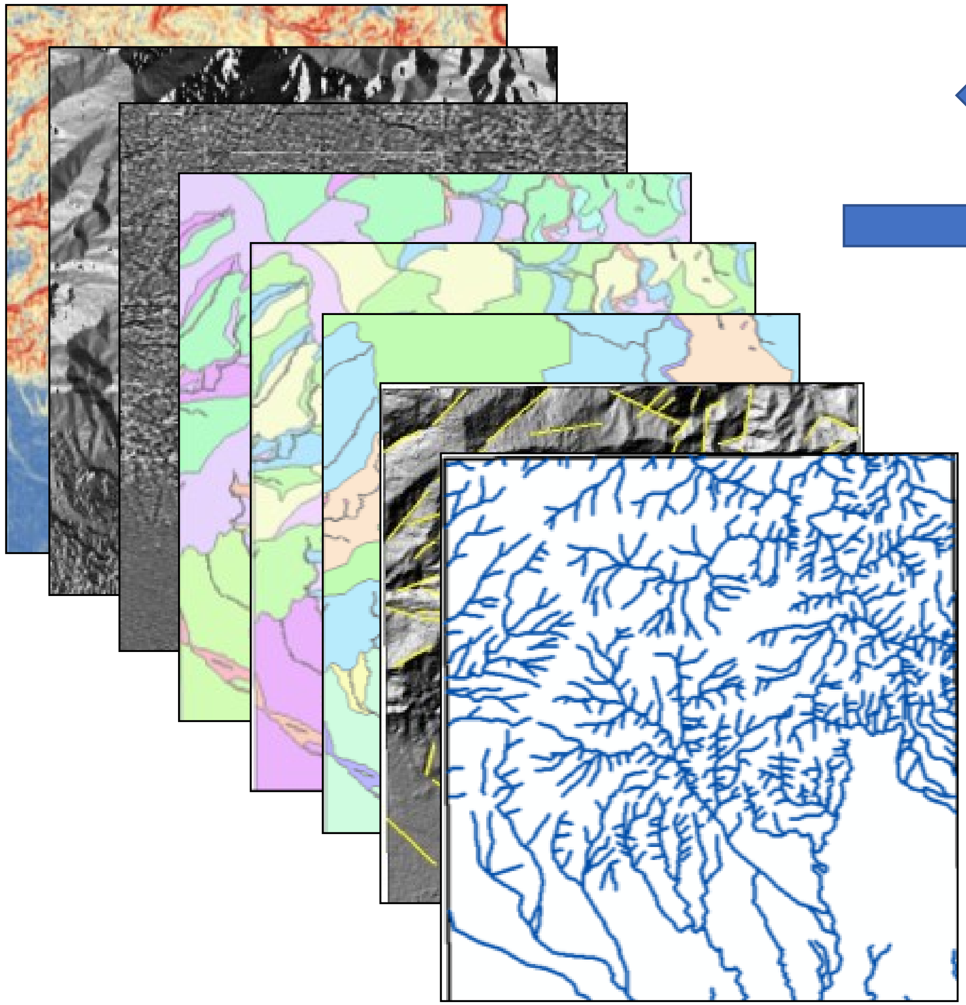
Methodology-Landslide dominant terrain

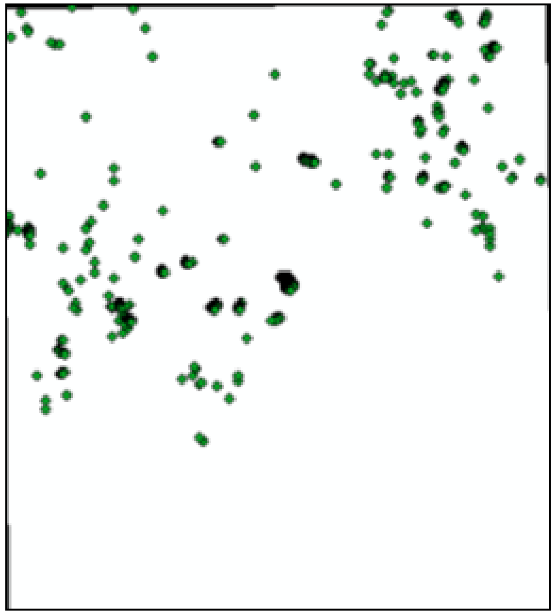


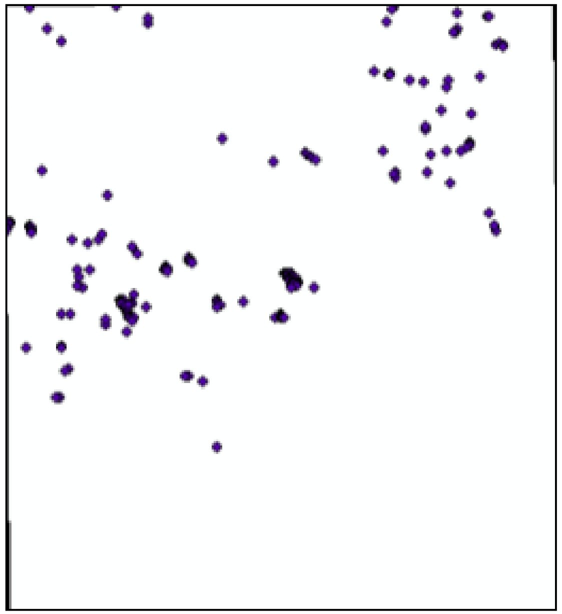
Methodology-Landslide dominant terrain

Geofactor Spatial Database



Landslide Spatial Database

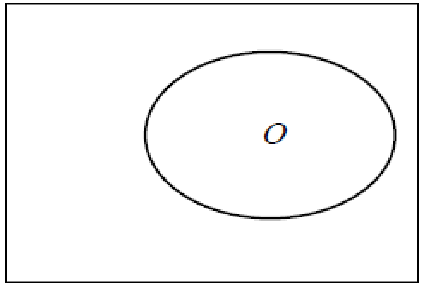




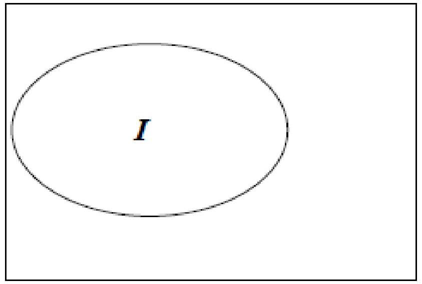
Methodology-Landslide dominant terrain

Mathematics/ Algorithm

Yule's Co-efficient (for Categorical Themes)
(Yule, 1912; Fleiss, 1991; Bonham-Carter, 1994)

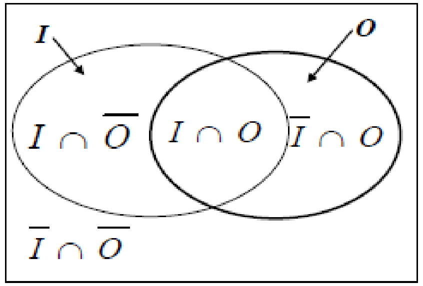


$T = 2945;\ O = 727$



$T = 2945;\ I = 486$

- O = known geo-object of interest
- I = indicator (or evidence) pattern
- T = study area



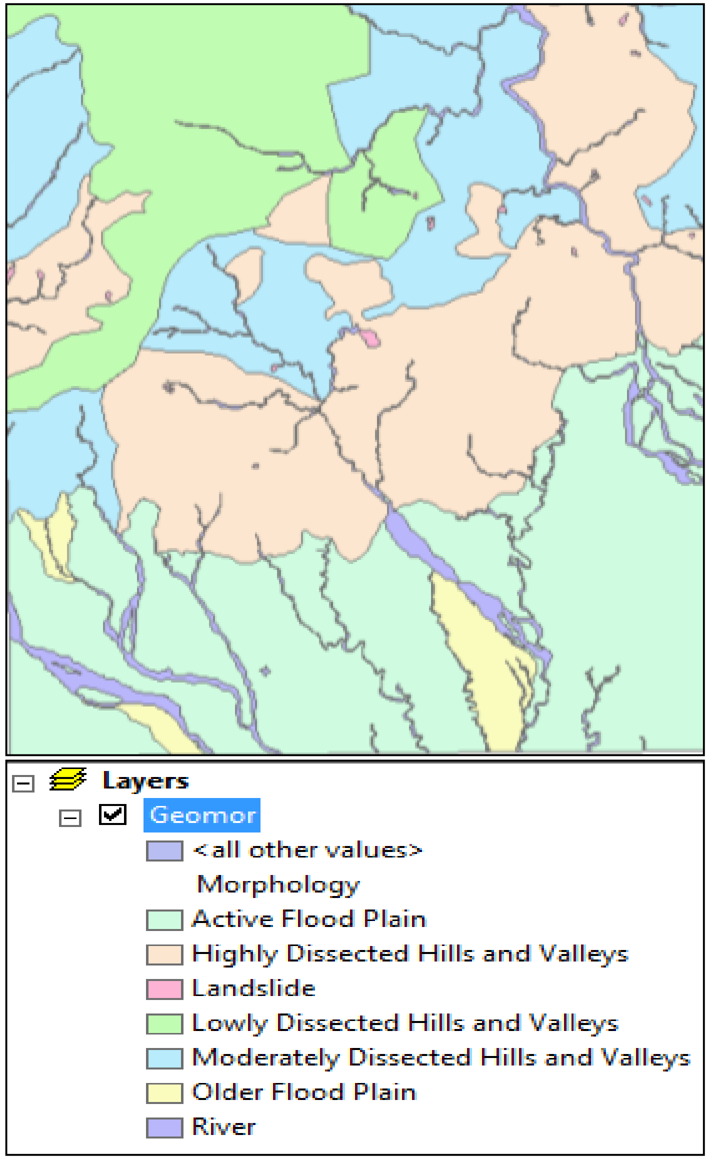
$$I \cap O = T_{11} = 345$$
$$I \cap \overline{O} = T_{21} = 141$$
$$\overline{I} \cap O = T_{12} = 382$$
$$\overline{I} \cap \overline{O} = T_{22} = 2077$$

- $T_{11} \rightarrow$ derived from cross operation
- $T_{12} = O - T_{11}$
- $T_{21} = I - T_{11}$
- $T_{22} = T - T_{11} - T_{12} - T_{21}$

Yc = (SQRT(T11/T21)-SQRT(T12/T22))/(SQRT(T11/T21)+SQRT(T12/T22))

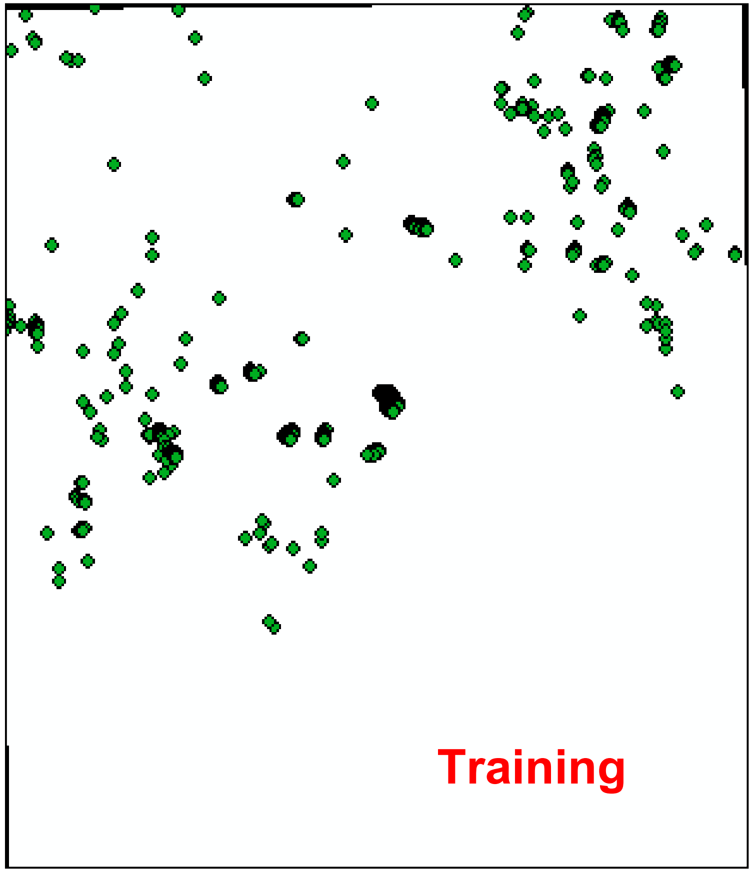
Note: an example of I is a slope aspect class

Methodology-Landslide dominant terrain



∩

Overlay

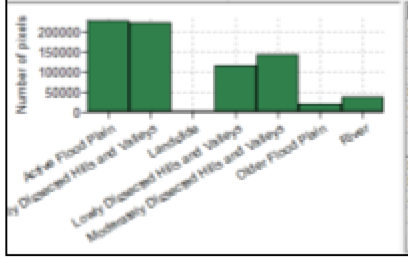


Example

Which Geomorphology classes have positive spatial association with landslides

Methodology-Landslide dominant terrain

Histogram Table of Geomorphology Theme (NpixC)



	npix	npixpct	pctnotund	Area
Active Flood Plain	227078	28.98	29.71	204370200
Highly Dissected Hills and Valleys	222887	28.44	29.16	200598300
Landslide	905	0.12	0.12	814500
Lowly Dissected Hills and Valleys	115470	14.74	15.11	103923000
Moderately Dissected Hills and Valleys	141876	18.11	18.56	127688400
Older Flood Plain	18936	2.42	2.48	17042400
River	37129	4.74	4.86	33416100
Min	905	0.12	0.12	814500
Max	227078	28.98	29.71	204370200
Avg	109183	13.94	14.29	98264700
StD	93983	11.99	12.29	84584531
Sum	764281	97.55	100.00	687852900

Cross Table of Geomorphology and Training Landslide Data (T11)

Dependent Table "GeomXLS" - TableCross(Geomorphology.mpr,LS.mpr,IgnoreUndefs) - ILWIS

	Geomorphology	LS	NPix	Area
Active Flood Plain * Slide	Active Flood	Slide	27	24300
Highly Dissected Hills and Valleys *	Highly Dissec	Slide	3170	2853000
Landslide * Slide	Landslide	Slide	29	26100
Lowly Dissected Hills and Valleys *	Lowly Dissect	Slide	1716	1544400
Moderately Dissected Hills and Valley	Moderately Di	Slide	2574	2316600
Older Flood Plain * Slide	Older Flood P	Slide	5	4500
River * Slide	River	Slide	266	239400

T12 = NpixLS – T11 T21 = NpixC– T11 T22 = NpixT – T11-T12-T21

	NpixC	NpixT	T11	T21	NpixLS	T12	T22	Yc	LOFS
Active Flood Plain	227078	764281	27	227051	7787	7760	529443	-0.835	0.00
Highly Dissected Hills and Val	222887	764281	3170	219717	7787	4617	536777	0.129	0.45
Landslide	905	764281	29	876	7787	7758	755618	0.285	1.00
Lowly Dissected Hills and Val	115470	764281	1716	113754	7787	6071	642740	0.117	0.41
Moderately Dissected Hills an	141876	764281	2574	139302	7787	5213	617192	0.193	0.68
Older Flood Plain	18936	764281	5	18931	7787	7782	737563	-0.727	0.00
River	37129	764281	266	36863	7787	7521	719631	-0.092	0.00
Min	905	764281	5	876	7787	4617	529443	-0.835	0.00
Max	227078	764281	3170	227051	7787	7782	755618	0.285	1.00
Avg	109183	764281	1112	108071	7787	6675	648423	-0.133	0.36
StD	93983	0	1356	93217	0	1356	93217	0.458	0.39
Sum	764281	5349967	7787	756494	54509	46722	4538964	-0.931	2.54

Yc = (SQRT(T11/T21)-SQRT(T12/T22))/(SQRT(T11/T21)+SQRT(T12/T22))

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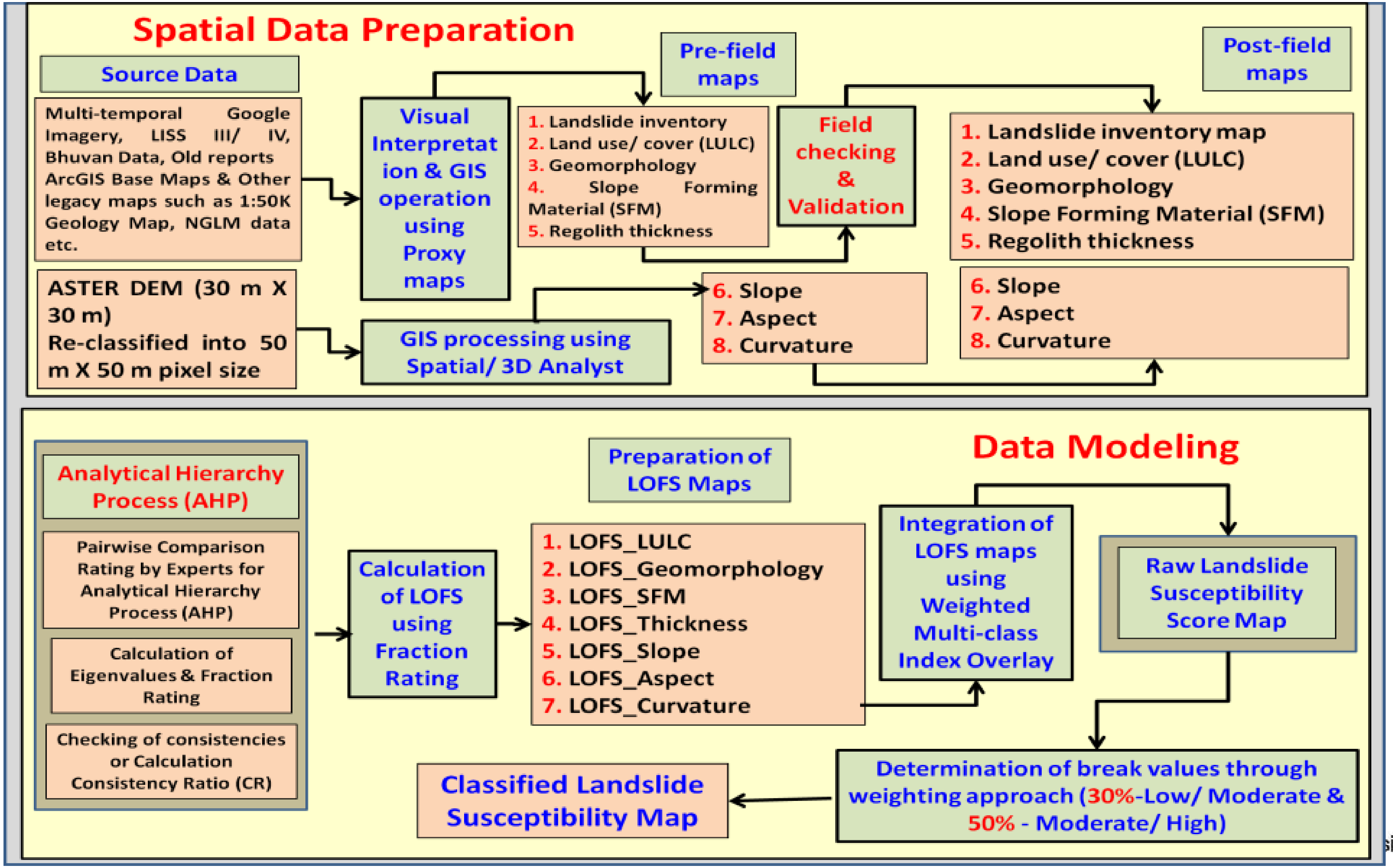
Methodology-Landslide deficient terrain



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Methodology-Landslide deficient terrain

Discussion to fix up pairwise comparison rating – expert-driven technique prior to application of AHP

Methodology-Landslide deficient terrain

Thematic classes and their mutual rankings (in a scale of 0 to 9) for preparation of knowledge-driven pairwise comparison matrix in AHP for states of Southern & Central Region (MH=Maharashtra, KG=Karnataka and Goa, TN=Tamil Nadu, Ker=Kerala).

	Curvature				
		MH	**KG**	**TN**	**Ker**
1	Concave (upto -0.1)	4	4	4	4
2	Flat (-0.1 to 0.1)	2	2	2	2
3	Convex (>0.1)	6	6	6	6
	Slope				
		MH	**KG**	**TN**	**Ker**
4	<15	2	2	2	2
5	15-25	4	4	4	6
6	25-35	9	8	8	8
7	35-45	8	6	6	4
8	>45	7	2	2	2
	Landuse/Landcover (LULC)				
		MH	**KG**	**TN**	**Ker**
9	Barren	2	1	0	2
10	Sparse Vegetation	6	7	5	4
11	Moderate Vegetation	6	5	5	6
12	Thick Vegetation	4	4	4	4
13	Fallow Land	1	1	1	1
14	Swamp	0	0	0	0
15	Mangroves	0	0	0	0
16	Salt pan	0	0	0	0
17	Barren Sand	0	0	0	0
18	Extensive Slope Cut	9	9	9	9
19	Quarry	2	5	2	2
20	Dumping Ground	6	6	6	6
21	Cultivation	3	2	3	2
22	Settlement	2	1	2	2
23	Settlement on modified slope	7	7	8	9
24	Plantation (LHP)	2	3	4	6
25	Plantation (HHP)	4	4	3	4

Pairwise comparison matrix prepared by experts/ workers

Methodology-Landslide deficient terrain

(AHP calculations)

B18 | f_x =B3/B15

Pairwise comparison rating matrix												
	CL	LHP	HHP	TV	MV	SV	SET	BR	WL	ESC	QR	JH
CL	1.00	2.00	0.50	1.00	0.33	0.20	0.50	0.25	0.20	0.13	0.25	0.20
LHP	0.50	1.00	0.33	0.50	0.25	0.17	0.33	0.20	0.17	0.11	0.20	0.17
HHP	2.00	3.00	1.00	2.00	0.50	0.25	1.00	0.33	0.25	0.14	0.33	0.25
TV	1.00	2.00	0.50	1.00	0.33	0.20	0.50	0.25	0.20	0.13	0.25	0.20
MV	3.00	4.00	2.00	3.00	1.00	0.33	2.00	0.50	0.33	0.17	0.50	0.33
SV	5.00	6.00	4.00	5.00	1.00	1.00	4.00	2.00	1.00	0.25	2.00	1.00
SET	2.00	3.00	1.00	2.00	0.50	0.25	1.00	0.33	0.25	0.14	0.33	0.25
BR	4.00	5.00	3.00	4.00	2.00	0.50	3.00	1.00	0.50	0.20	1.00	0.50
WL	5.00	6.00	4.00	5.00	3.00	1.00	4.00	2.00	1.00	0.25	2.00	1.00
ESC	8.00	9.00	7.00	8.00	6.00	4.00	7.00	5.00	4.00	1.00	5.00	4.00
QR	4.00	5.00	3.00	4.00	2.00	0.50	3.00	1.00	0.50	0.20	1.00	0.50
JH	5.00	6.00	4.00	5.00	3.00	1.00	4.00	2.00	1.00	0.25	2.00	1.00
SUM	40.50	52.00	30.33	40.50	21.92	9.40	30.33	14.87	9.40	2.96	14.87	9.40

For 1st Table, always consider row criteria with respect to column criteria

For 2nd Table, eigenvalues of each column are obtained after

16	Calculation of eigenvalues, fraction rating and LOFS													
17		CL	LHP	HHP	TV	MV	SV	SET	BR	WL	ESC	QR	JH	Frac Rate	LOFS
18	CL	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.02	0.02	0.02297187	0.08
19	LHP	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.04	0.01	0.02	0.01624147	0.05
20	HHP	0.05	0.06	0.03	0.05	0.02	0.03	0.03	0.02	0.03	0.05	0.02	0.03	0.03483679	0.12
21	TV	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.02	0.02	0.02297187	0.08
22	MV	0.07	0.08	0.07	0.07	0.05	0.04	0.07	0.03	0.04	0.06	0.03	0.04	0.05270452	0.18
23	SV	0.12	0.12	0.13	0.12	0.14	0.11	0.13	0.13	0.11	0.08	0.13	0.11	0.11962365	0.40
24	SET	0.05	0.06	0.03	0.05	0.02	0.03	0.03	0.02	0.03	0.05	0.02	0.03	0.03483679	0.12
25	BR	0.10	0.10	0.10	0.10	0.09	0.05	0.10	0.07	0.05	0.07	0.07	0.05	0.07869444	0.26
26	WL	0.12	0.12	0.13	0.12	0.14	0.11	0.13	0.13	0.11	0.08	0.13	0.11	0.11962365	0.40
27	ESC	0.20	0.17	0.23	0.20	0.27	0.43	0.23	0.34	0.43	0.34	0.34	0.43	0.29917688	1.00
28	QR	0.10	0.10	0.10	0.10	0.09	0.05	0.10	0.07	0.05	0.07	0.07	0.05	0.07869444	0.26
29	JH	0.12	0.12	0.13	0.12	0.14	0.11	0.13	0.13	0.11	0.08	0.13	0.11	0.11962365	0.40
30														0.29917688	

Fraction Rate = Sum of row/ no of criteria
Excel formula of the 1st Cell = 0.2+0.04+0.02+...+0.02+0.02)/12

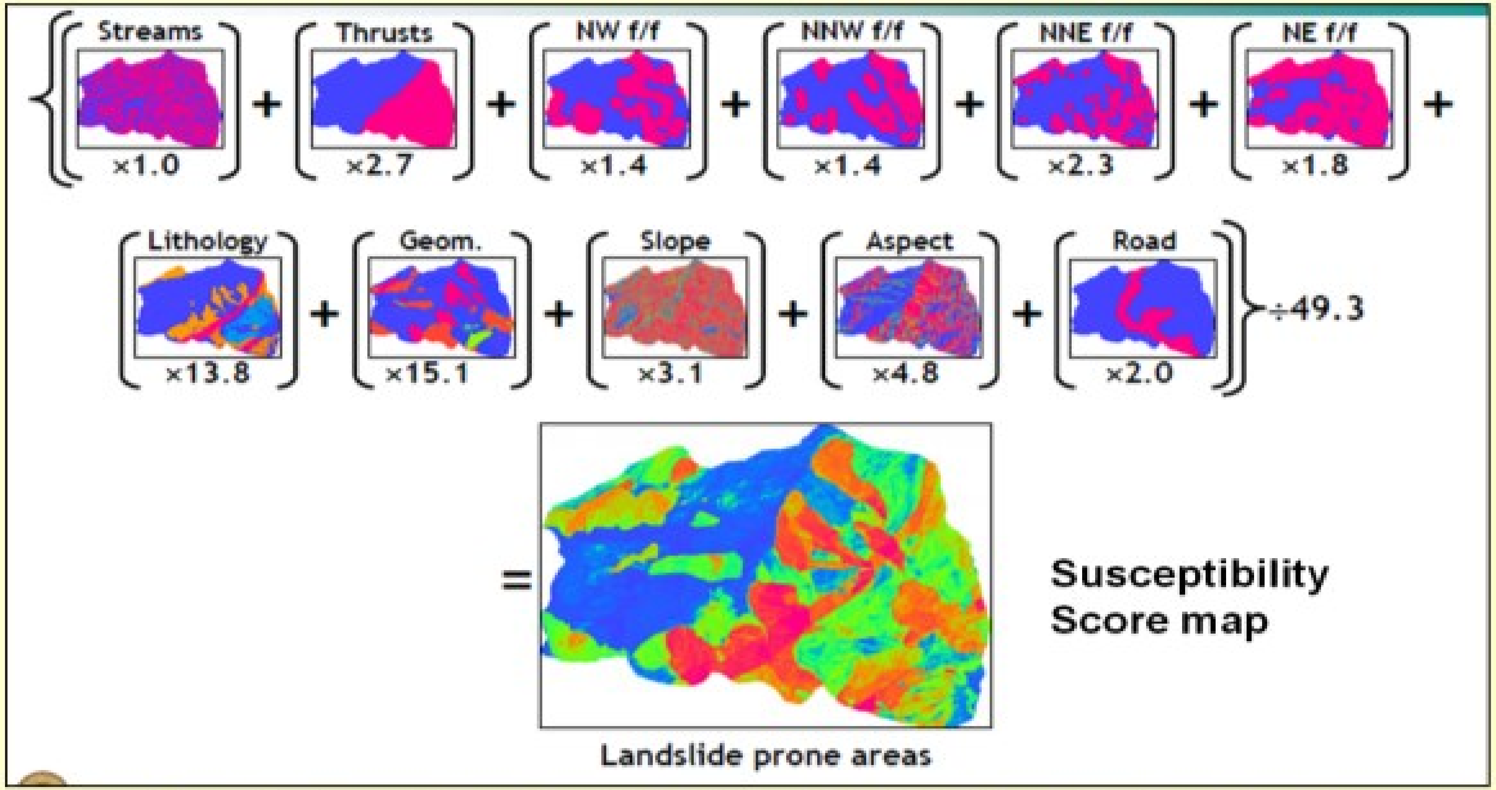
LOFS = Fraction Rate/ Max (Fraction Rate)
Excel formula of the 1st Cell = Cell No/Max (Cell 1:Cell12 of the Fraction Rate Column)

Determination of Ratings and Weights

Weighted Multi-class Index Overlay

- Multi-class predictor maps, S_i, are combined using the following equation, which calculates an average score, $\overline{S}$, for every location (or pixel):

$$\overline{S} = \frac{\sum_{i}^{n} S_{ij} W_i}{\sum_{i}^{n} W_i}$$



Final integration for Weighted Multi-class Index Overlay

Map Integration

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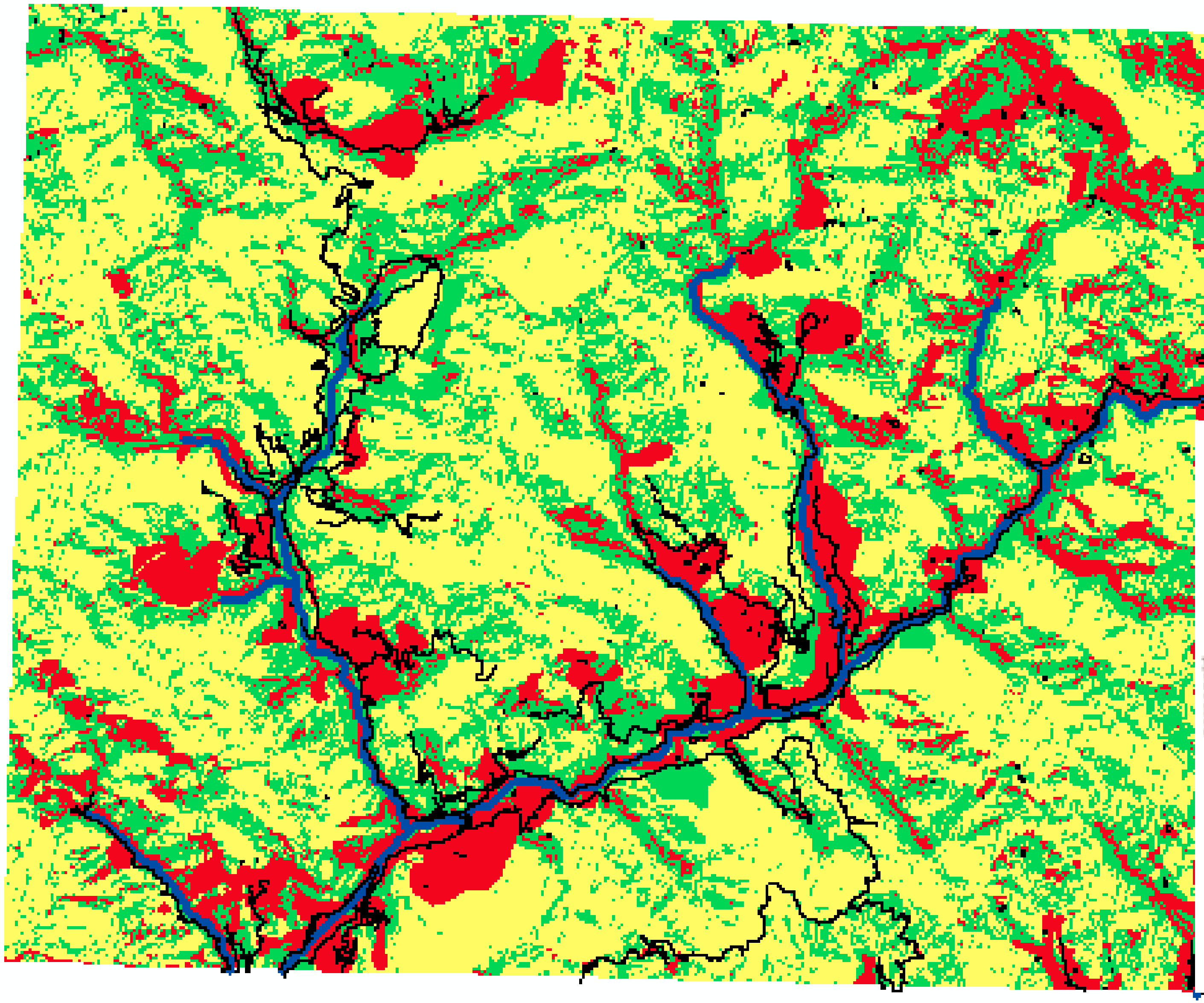
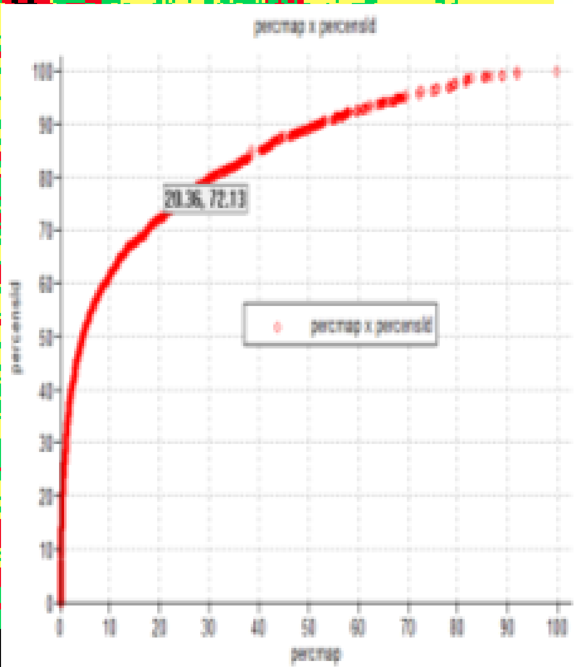
Landslide Susceptibility Map and Validation





Red – High; Green – Moderate & Yellow – Low;

Landslides: What tool we already have

GSI's National Landslide Susceptibility Mapping (NLSM) Project (2014-2022)

An excellent spatial forecasting tool for landslides

Total NLSM Target = **434**k sq. km

Mapping completed till **March 2020** = **363**k sq. km **(~85%)**

Data uploaded in Bhukosh Portal for free download and use by all

- ✓ NLSM Maps = **363**k sq. km. (**85%** of total target)
- ✓ Landslide polygons mapped = **61,287 nos.**
- ✓ Landslide inventory with detailed field based attributes = **28,831 nos.**

Landslides: Scenario in India

Northwestern Himalayas						
State/ UT	**Target area proposed (km^2)**	**Target area mapped so far (km^2)**	**Landslide polygons mapped (Nos.)**	**Landslides field validated (Nos.)**	**High Susceptible %**	**Landslide No Density %**
Himachal Pradesh	42100	42108	17127	6420	**26**	**41**
Jammu & Kashmir (UT) & Ladakh (UT)	68700	68955	8303	2340	17	12
Uttarakhand	39000	39009	14782	4927	**22**	**38**
Total	**149800**	**150072**	**40212**	**13687**	**22**	**27**

Eastern Himalayas						
State	**Target area proposed (km^2)**	**Target area mapped so far (km^2)**	**Landslide polygons mapped (Nos.)**	**Landslides field validated (Nos.)**	**High Susceptible %**	**Landslide No Density %**
Sikkim	4980	4979	3379	651	17	68
West Bengal	2970	2980	1554	1529	17	52
Total	**7950**	**7959**	**4933**	**2180**	**17**	**62**

Landslides: Scenario in India

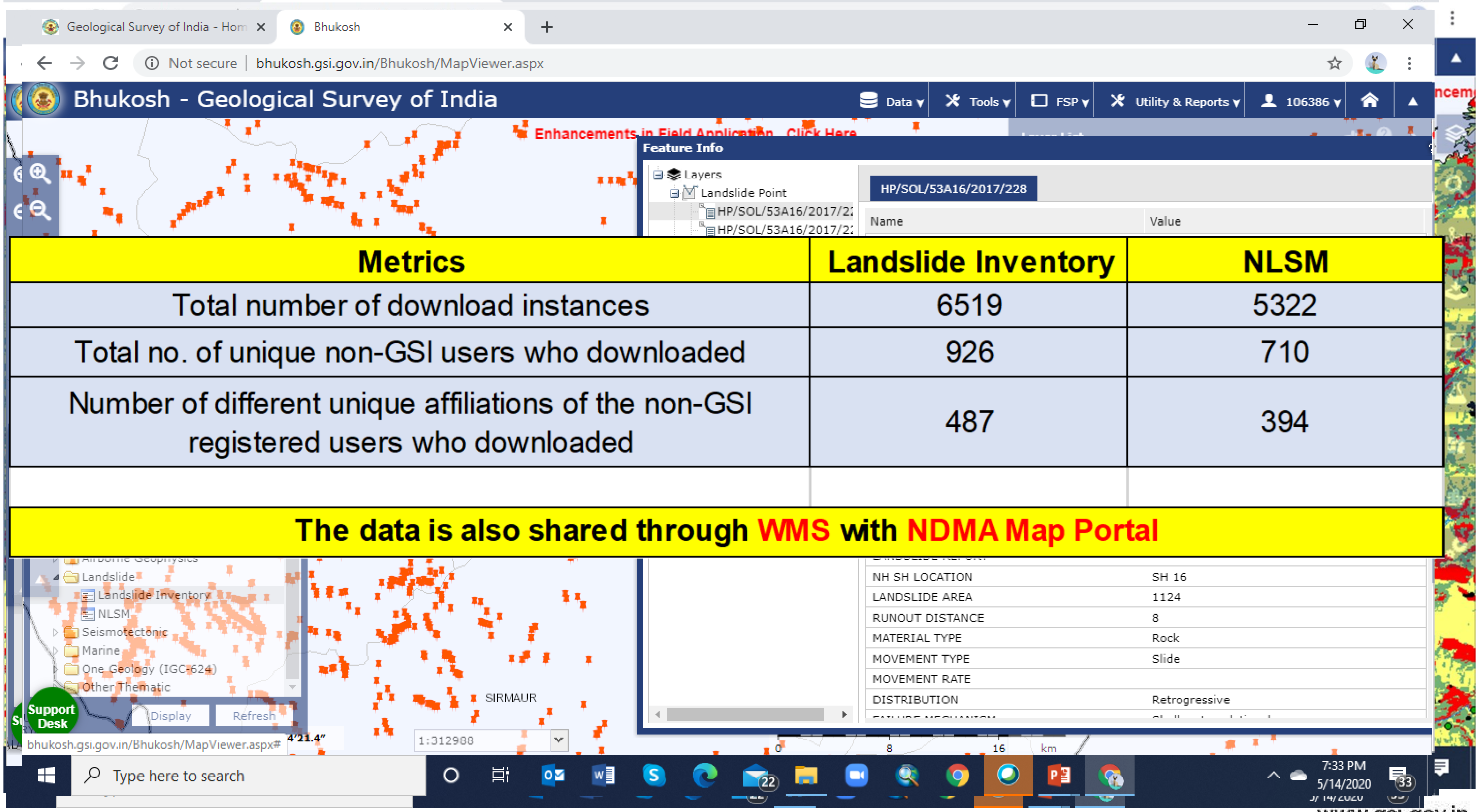
Northeastern Himalayas & Sub-Himalayana Region						
State	**Target area proposed (km^2)**	**Target area mapped so far (km^2)**	**Landslide polygons mapped (Nos.)**	**Landslides field validated (Nos.)**	**High Susceptible %**	**Landslide No Density %**
Arunanchal Pradesh	71210	**Mapping in progress; completion by March 2022**				
Assam	24100	24144	527	598	2	2
Meghalaya	22020	22601	1525	791	1	7
Mizoram	21040	21864	4221	2003	**18**	**19**
Tripura	1300	1367	57	56	2	4
Manipur	22500	23250	2405	1548	**14**	**10**
Nagaland	16320	17294	2742	1554	**16**	**16**
Total	**178490**	**110520**	**11477**	**6550**	**9**	**10**

Landslides: Scenario in India

Western & Eastern Ghats						
State	**Target area proposed (km^2)**	**Target area mapped so far (km^2)**	**Landslide polygons mapped (Nos.)**	**Landslides field validated (Nos.)**	**High Susceptible %**	**Landslide No Density %**
Maharashtra	28190	29191	1134	1152	3.68	4
Karnataka & Goa	34160	34869	1324	1324	6.65	4
Tamil Nadu	10080	10549	782	863	6.64	8
Kerala	19330	19301	1396	3016	11.29	16
Andhra Pradesh	1150	1124	29	29	6.26	3
Total	**92910**	**95034**	**4665**	**6384**	**7**	**7**

National geodatabase in public domain

(http://bhukosh.gsi.gov.in/Bhukosh/Public)



Metrics	Landslide Inventory	NLSM
Total number of download instances	6519	5322
Total no. of unique non-GSI users who downloaded	926	710
Number of different unique affiliations of the non-GSI registered users who downloaded	487	394

The data is also shared through WMS with NDMA Map Portal

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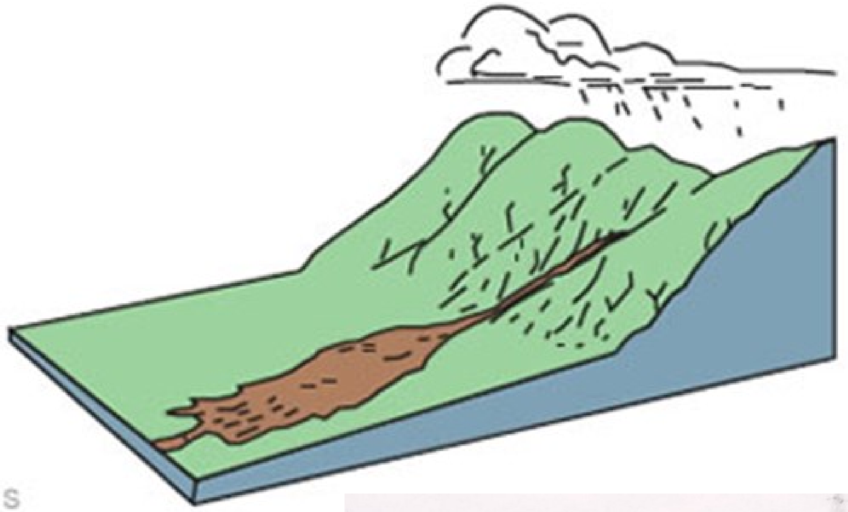
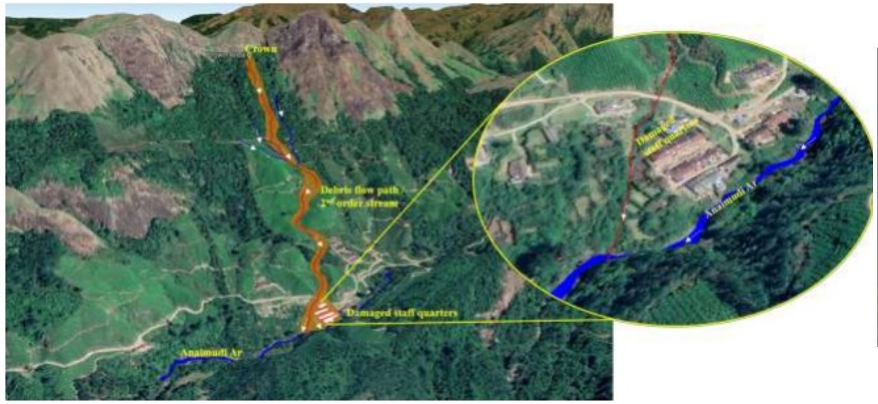
Landslide Runout Hazards



USGS

Malin Landslide, Pune: 2014, 151 people died

Mirik landslide, Darjeeling: In 2015, 19 people died



Pettimudi Debris Flow, Idukki, Kerala (06.08.2020) 66 people died

Source: SU: Kerala, GSI

Debris Flow Modeling

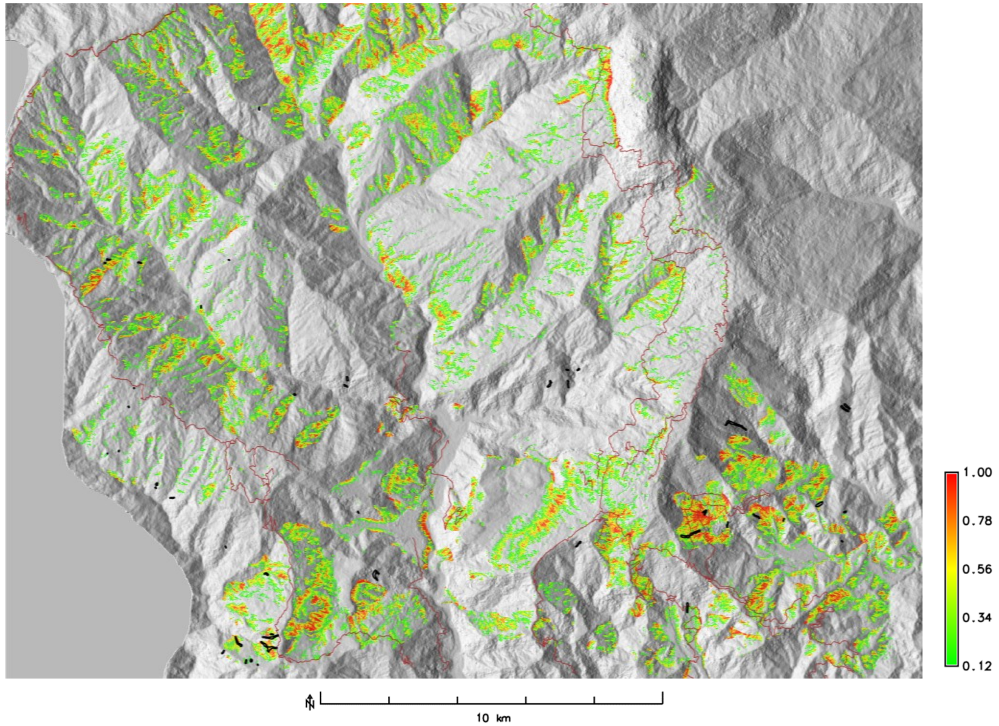
CONCEPTUAL MODELS

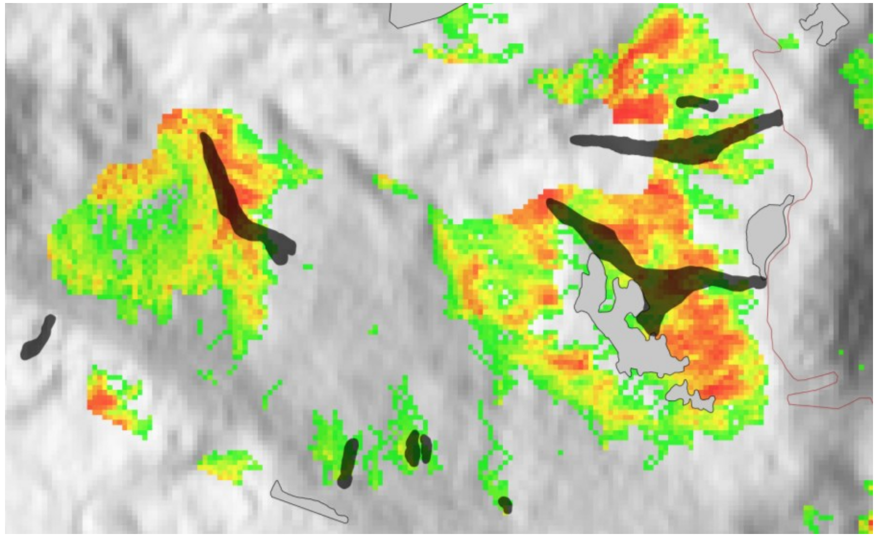
Spatial landslide susceptibility at catchment or regional scales are useful for hazard indication zoning and for prioritizing target areas for risk mitigation.

PHYSICAL BASED MODELS

- Usually employed at slope scale
- Requires physical parameter of the material like type of material, its shear strength, porosity and permeability, volume etc.
- Limited to a single slope and a highly site-specific deterministic approach

Debris Flow Modeling (Conceptual Model)





Source data

1) Debris flow inventory
2) Very high resolution DEM
3) Slope Forming Map

Methodology

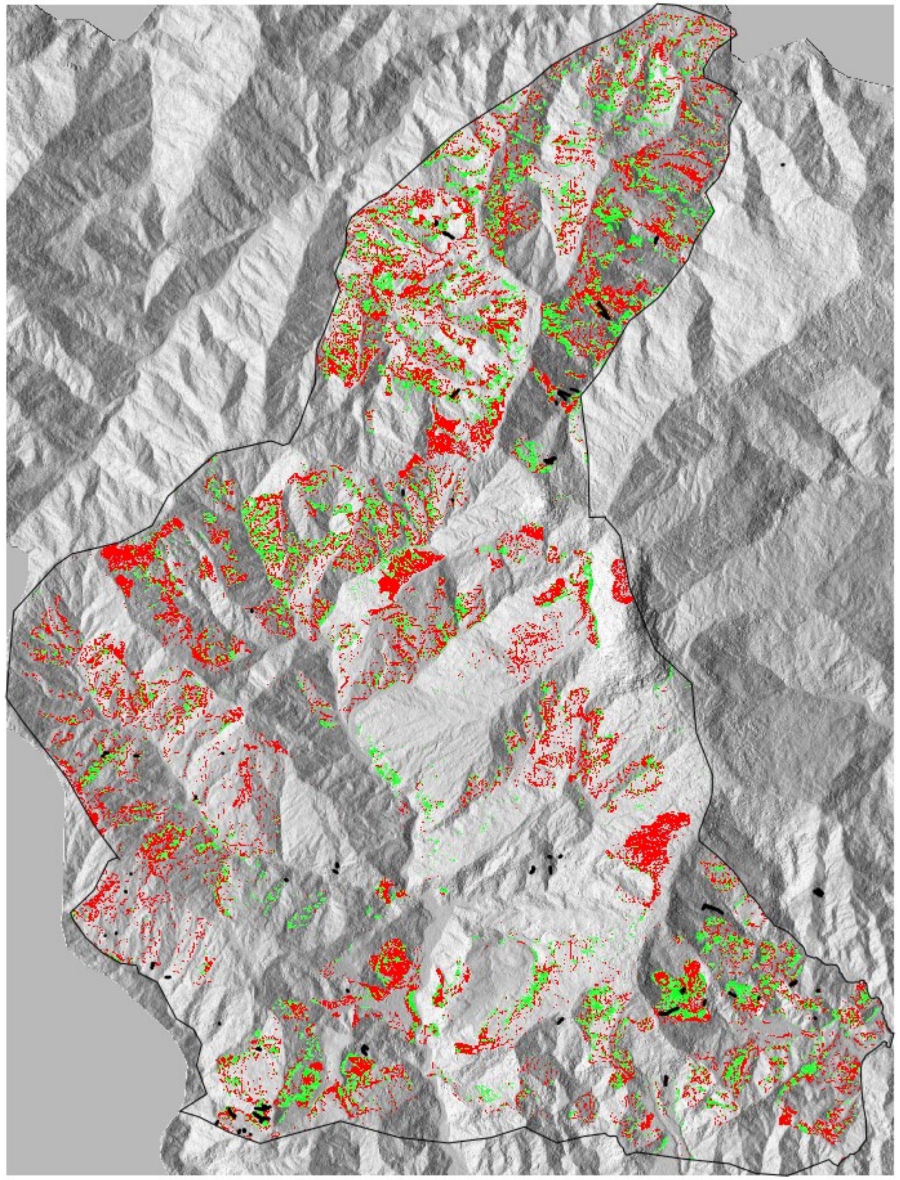
1) We delineate source area from the known debris flow inventory and/ or identify possible debris accumulated zone as potential source area

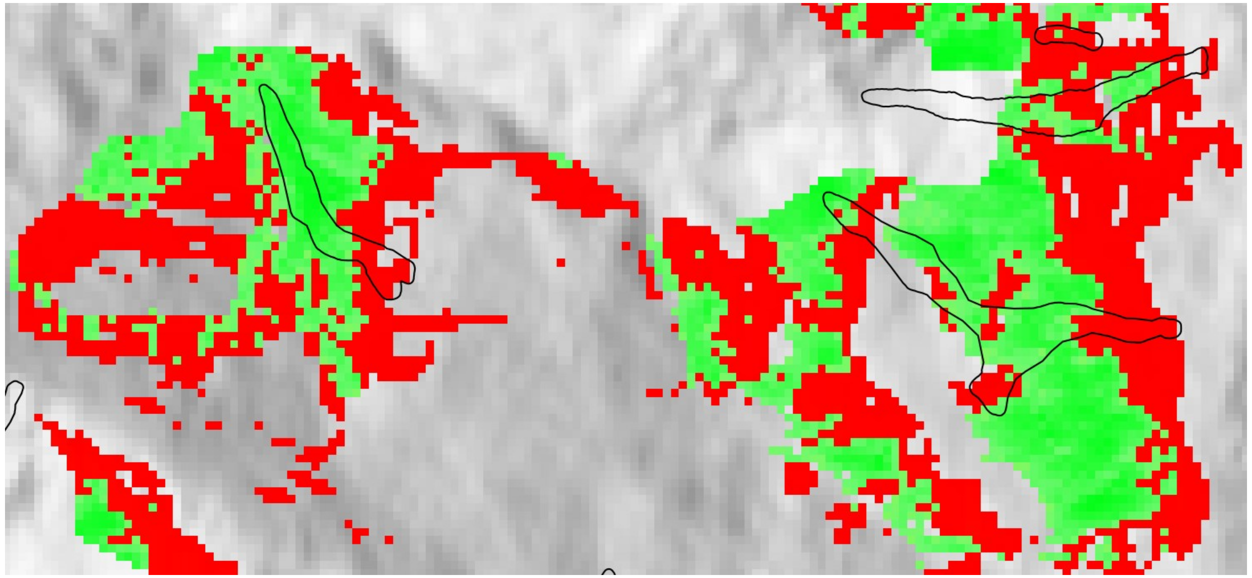
2) Define Topographic parameters from DEM of the source area and possible stopping location by running ***r.randomwalk*** conceptual model developed by ***Mergili, Krenn, and Chu, 2015***

3) Determine the probability of impact of pixel by possible debris flow, following Monte Carlo Simulation

Generation of Combined Susceptibility Model

(Initiation/ Source + Runout)





High Initiation susceptibility

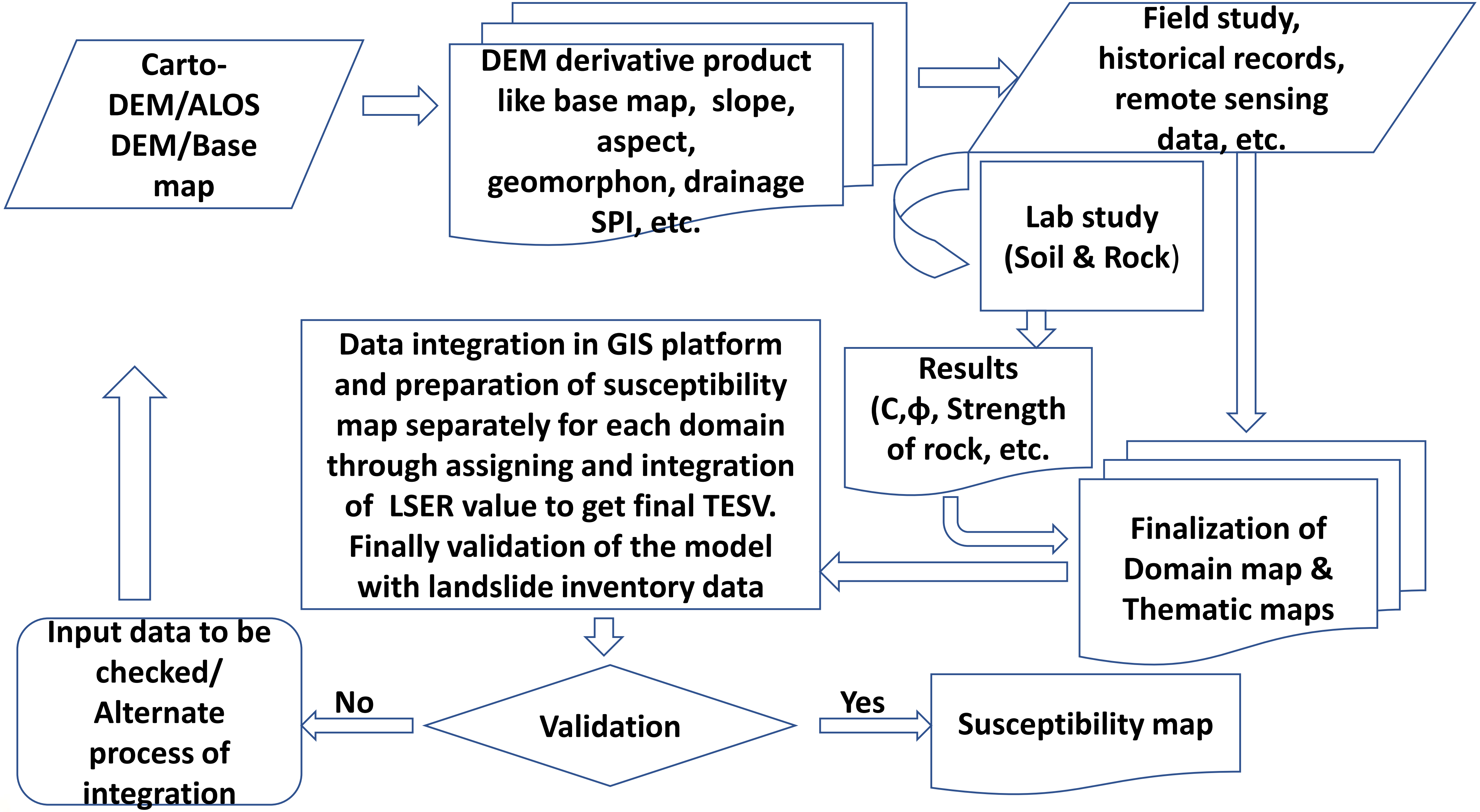
High Runout susceptibility (From Debris Flow Impact Probability Map)

Methodology: LSA (Meso scale 1:10,000)

- This is mostly being carried out through knowledge-driven technique only
- Recently, GSI has finalised a methodology after carrying out five pilot studies in different terrains.

At this scale, the area to be studied is much smaller (~30-50 sq. km.) and more reliance is given on **field inputs** only

Methodology: LSA (Meso scale 1:10,000)



Concept of landslide domain

Sr. No	Class	Criteria used for mapping
1	Debris	Areas occupied by overburden-covered slopes comprises of colluvium, compact debris, loose debris, slope wash, regolith.
2	Earth failure domain	Areas occupied by overburden-covered slopes comprises of soil.
3	Rock failure domain	Areas with rock cover
4	Cut slope failure domain	Buffers of 25 m, 50 m & 75 m of NH, SH and important roads in Low, moderate and highly dissected geomorphological terrain respectively on the basis of visibility at the field.
5	No landslide domain	These are the areas where there is no chance of initiation of landslide like the one alluvium material (sandy) deposited within the river channel and water body.

Mapping Units and Geofactors

Geofactor	Remarks
Mapping Unit	Pixel (10 m/ 12.5 m) or Slope Facet
Slope Morphometry Factors	Derived maps from either 10 m CartoDEM or 12.5 m Alos Pulsar DEM
Landslide inventory	Prepare from all the sources (Remote Sensing, Field, Legacy reports, Media reports, reports from other departments etc.)
Slope forming material (SFM) map	Theme should be prepared/ confirmed through direct field inputs only, Prepare geotechnical map using SFM (Kumar et. al, 2019, GSI Report)
Hydrology map	Take the point data of hydrology condition of the slope e.g. dripping, flowing condition
Land use/land cover map	Prepared during pre-field but field validated
Structural data	RMR, Kinematic analysis, Kinematic failure map
Field sample (Rock and soil)	Sample (Approx. 5kg overburden sample, weight the overburden sample immediately to know the wet weight for further calculation of the Natural moisture content)
Geotechnical map	SFM, Rock Mass Rating (RMR) for rock, C & Ø for overburden (Other field parameters for extrapolation of the polygon)

Map Weights

Rock Slide	
Factors	Weightage
1. Geotechnical map (GT)	0.6
2. Kinematic failure (KF)	0.4
Total Estimated Susceptibility Values (TESV)	1.0
Rock fall	
1. Geotechnical map (GT)	0.4
2. Toppling failure (TF)	0.4
3.LULC	0.2
Total Estimated Susceptibility Values (TESV)	1.0

Debris/Earth slide	
Factors	Weightage
1. Geotechnical map (GT)	0.5
2. Landform (LF)	0.3
3. Stream Power Index (SPI)	0.1
4. LULC	0.1
Total Estimated Susceptibility Values (TESV)	1.0
Cut-slope failure	
1. Regolith thickness (RT)	0.2
2. Slope map(S)	0.2
3. Geotechnical map (GT)	0.4
4. Relative Relief (RR)	0.2
Total Estimated Susceptibility Values (TESV)	1.0

For Rock Fall	
Geotechnical map(GT)	
Very good	0.2
good	0.4
fair	0.6
bad	0.8
Very bad	1.0
Toppling failure map(T)	
1 critical condition	0.8
2 critical condition	1.0

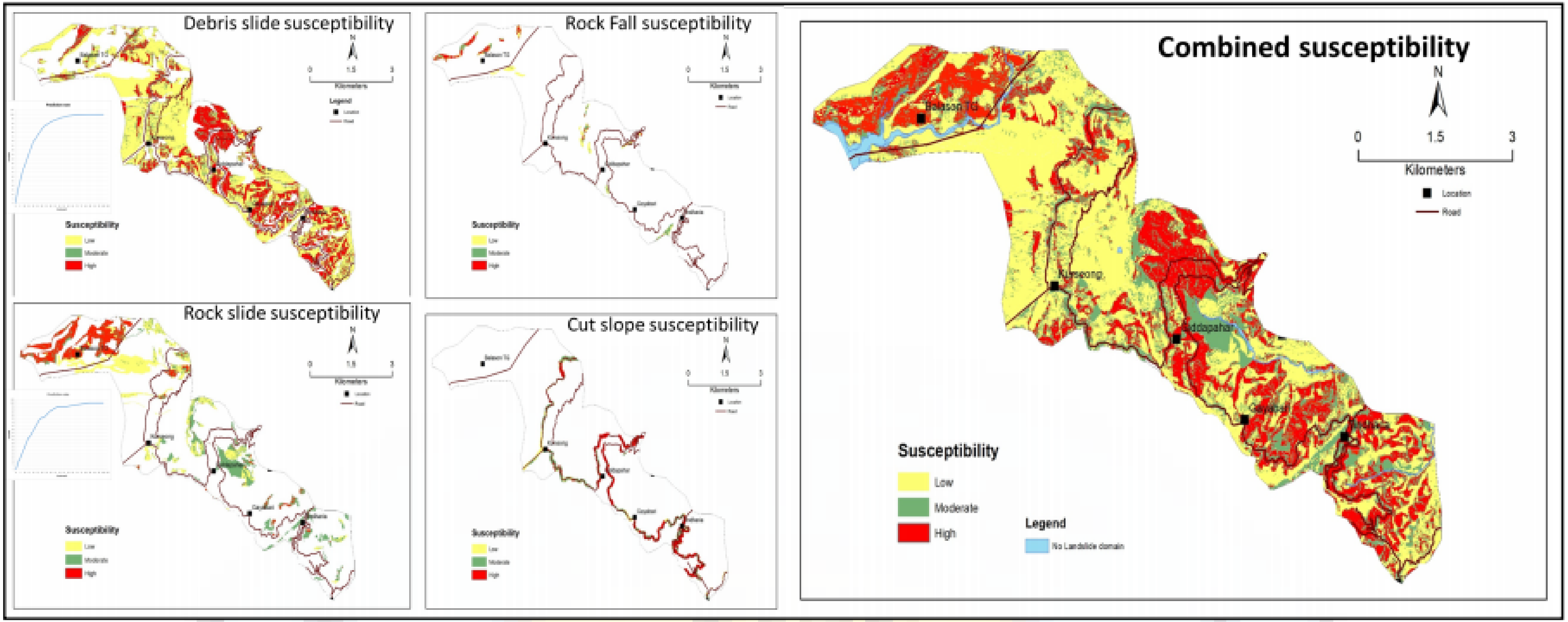
For Rock slide	
Geotechnical map (GT)	
Very good	0.2
Good	0.4
Fair	0.6
Bad	0.8
Very bad	1.0
Kinematic failure map (KF)	
1 critical condition	0.2
2 critical condition	0.4
3 critical condition	0.6
4 critical condition	0.8
5 critical condition	1.0

For (Debris/ Earth Slide)	Stream power Index (SPI)
0-1(very low erosion)	0.2
1-2(low erosion)	0.4
2-5(moderate erosion)	0.6
5-10(High erosion)	0.8
>10(very high erosion)	1.0
Landform map (LF)	
Flat	0.2
Ridge & depression	0.4
Shoulder, Spur & footslope	0.6
Slope	0.8
Hollow	1.0
Landuse/Landcover (LULC)	
Thick vegetation	0.2
Moderate vegetation	0.4
Tea plantation, cultivation and grassland	0.6
Sparse vegetation	0.8
Barren	1.0
Geotechnical map (GT)	
Very good	0.2
good	0.4
fair	0.6
bad	0.8

Cut slope	
Regolith thickness (RT)	
0-1	0.2
1-2	0.4
2-5	0.8
>5	1.0
Relative Relief map (RR)	
0-25 m	0.2
25-50 m	0.4
50-75 m	0.6
75-100 m	0.8
>100 m	1.0
Geotechnical map (GT)	
Very good	0.2
good	0.4
fair	0.6
bad	0.8
Very bad	1.0
Slope angle(S)	
0-15	0.2
15-25	0.4
25-35	0.6
35-45	0.8

Ratings & Weights

Final landslide susceptibility map (1:10,000)



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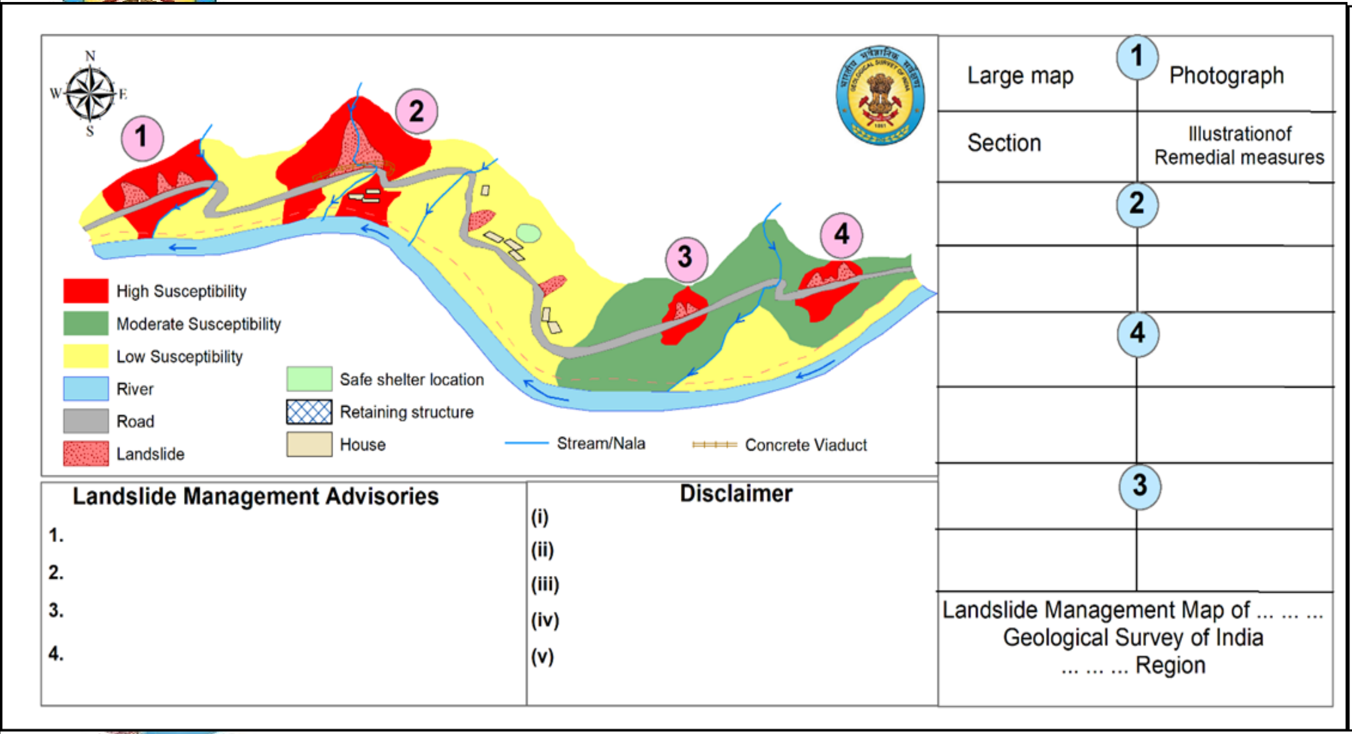
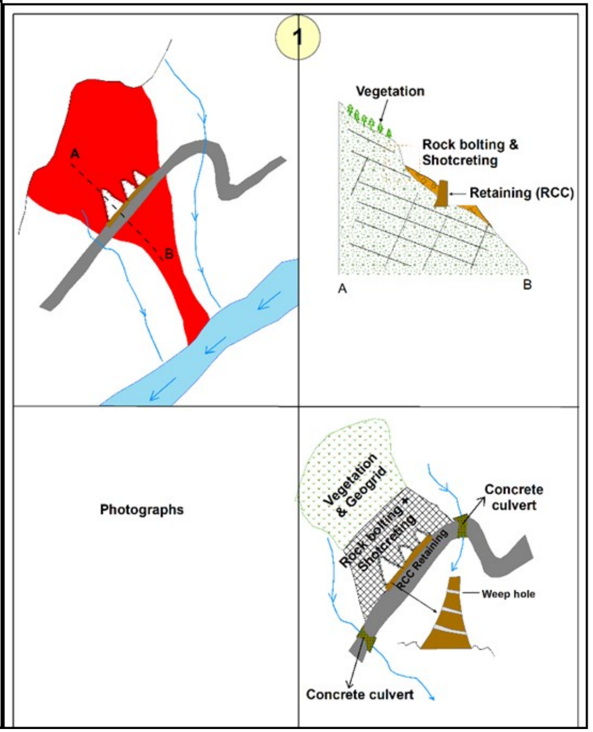
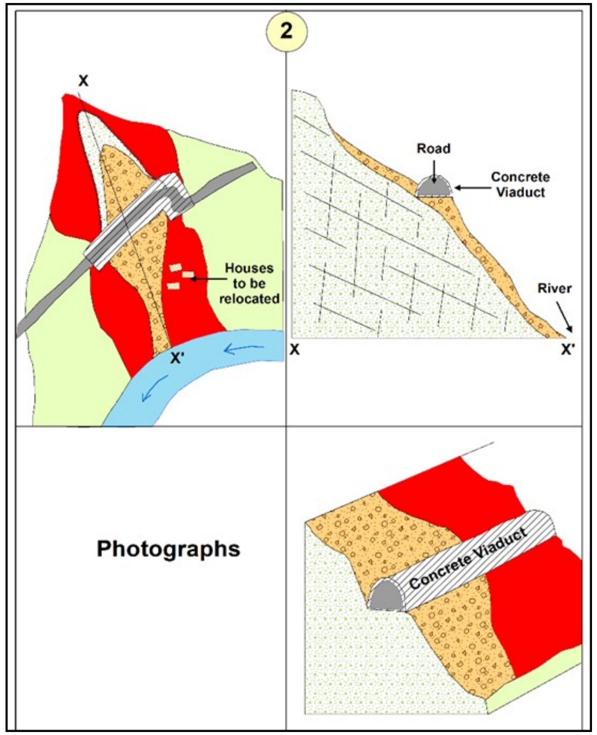
Landslide management map (1:10,000)







Landslide Management Advisory (1)

1. Provision of RCC Retaining Wall on hillside
2. Nala training 2 nos. with concrete culverts
3. Weep holes for drainage and hillside lined drains on road bench
4. On bare loosened rock face, Rock bolting and SFRS

Landslide Management Advisory (2)

1. Concrete viaduct/ tunnel for permanently avoiding the rockfall zone
2. Settlements/ Houses to be relocated

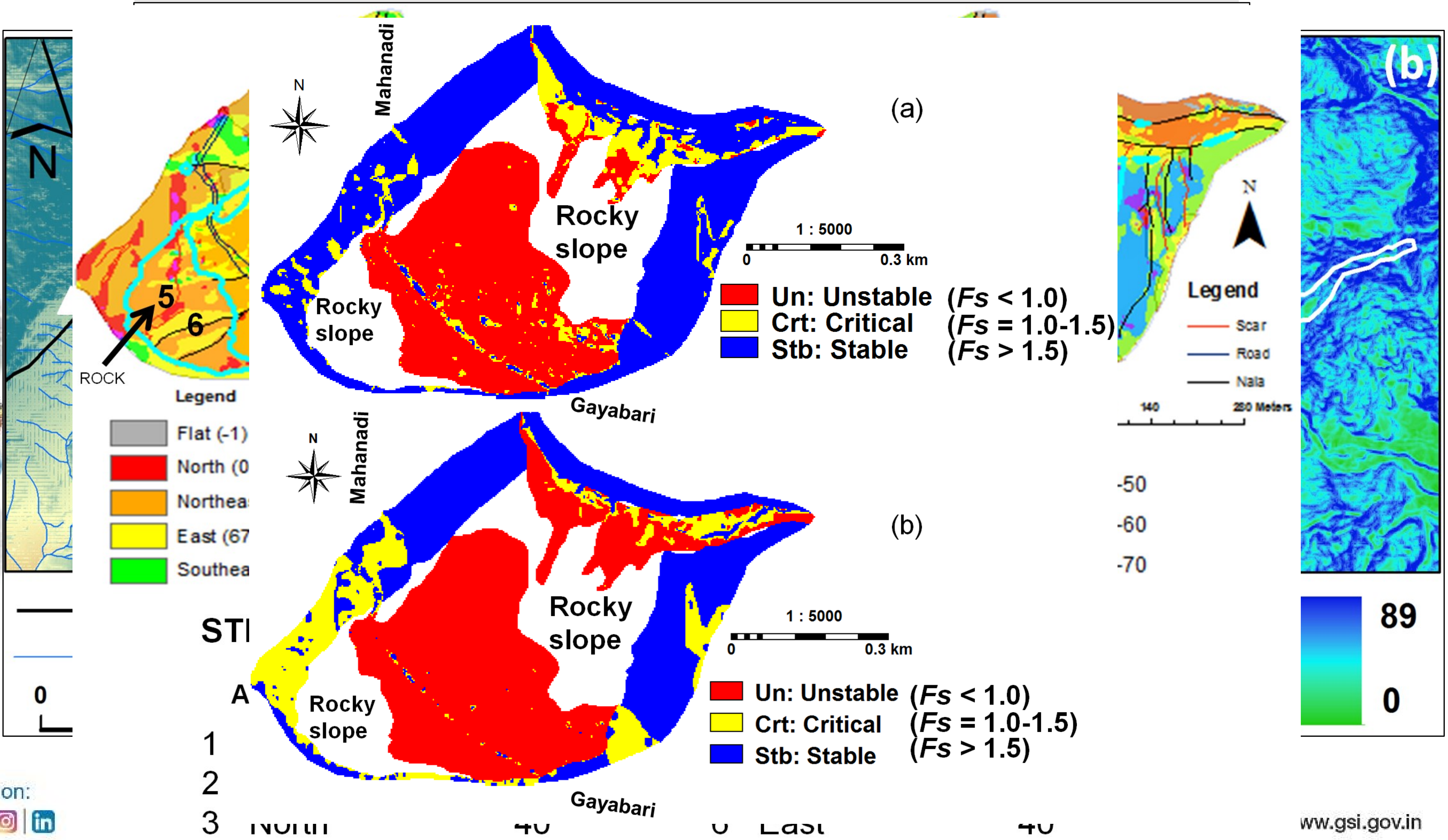
Disclaimer (1)

1. RCC Retaining structure to be designed based on insitu conditions
2. SFRS and Rock Bolting pattern to be decided after consultation of site geologists and engineers
3. Nala training and culverts to be constructed as per available site conditions

Disclaimer (2)

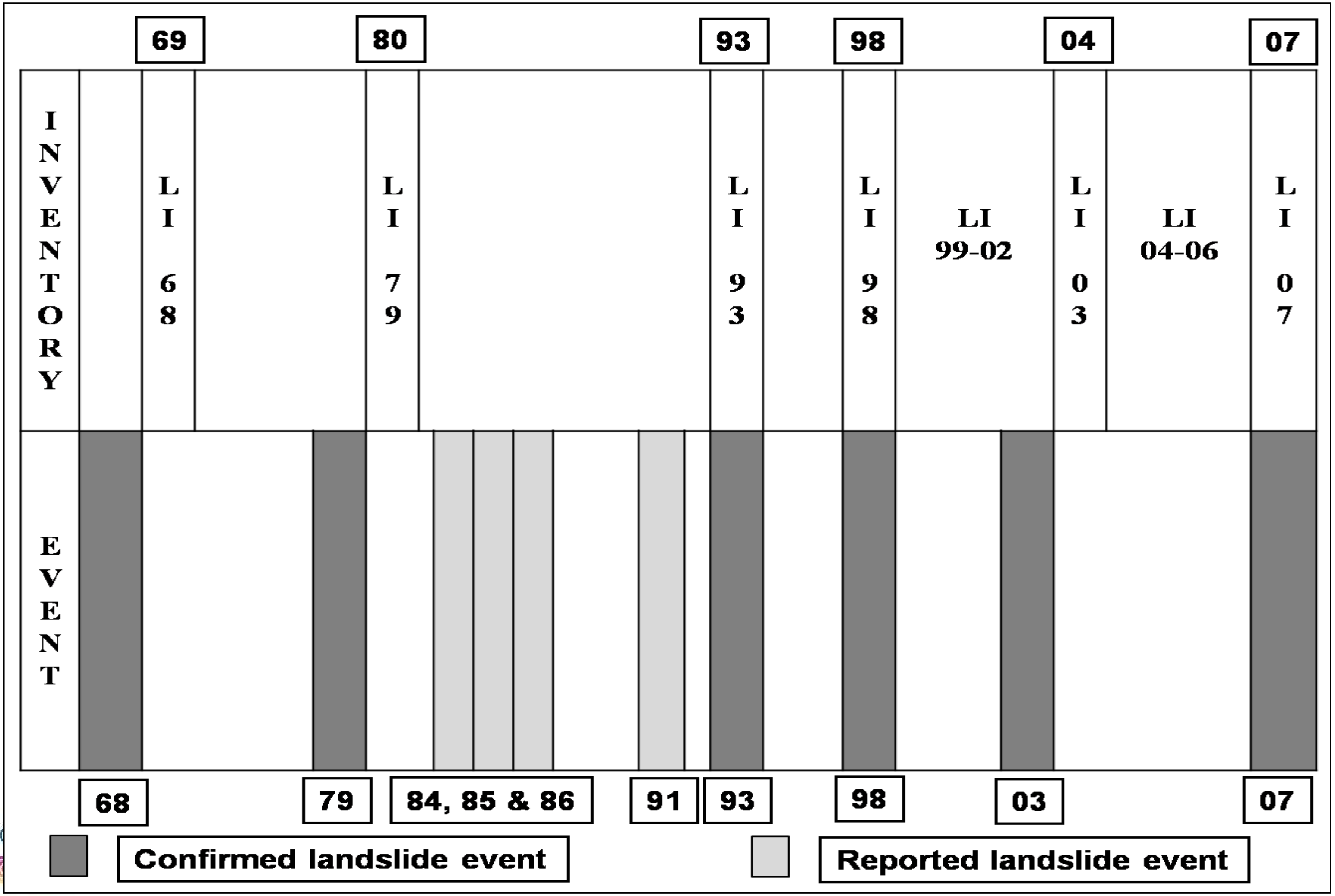
1. Concrete viaduct to be designed after consulting insitu condition, rockfall impact analysis, and rock fall modeling after consulting a suitable Geotechnical Engineer

Methodology: LSA (Site Specific Scale 1:1,000)



Landslide Hazard & Risk Analysis – not a trivial task!!!

Landslide Inventory & Classification



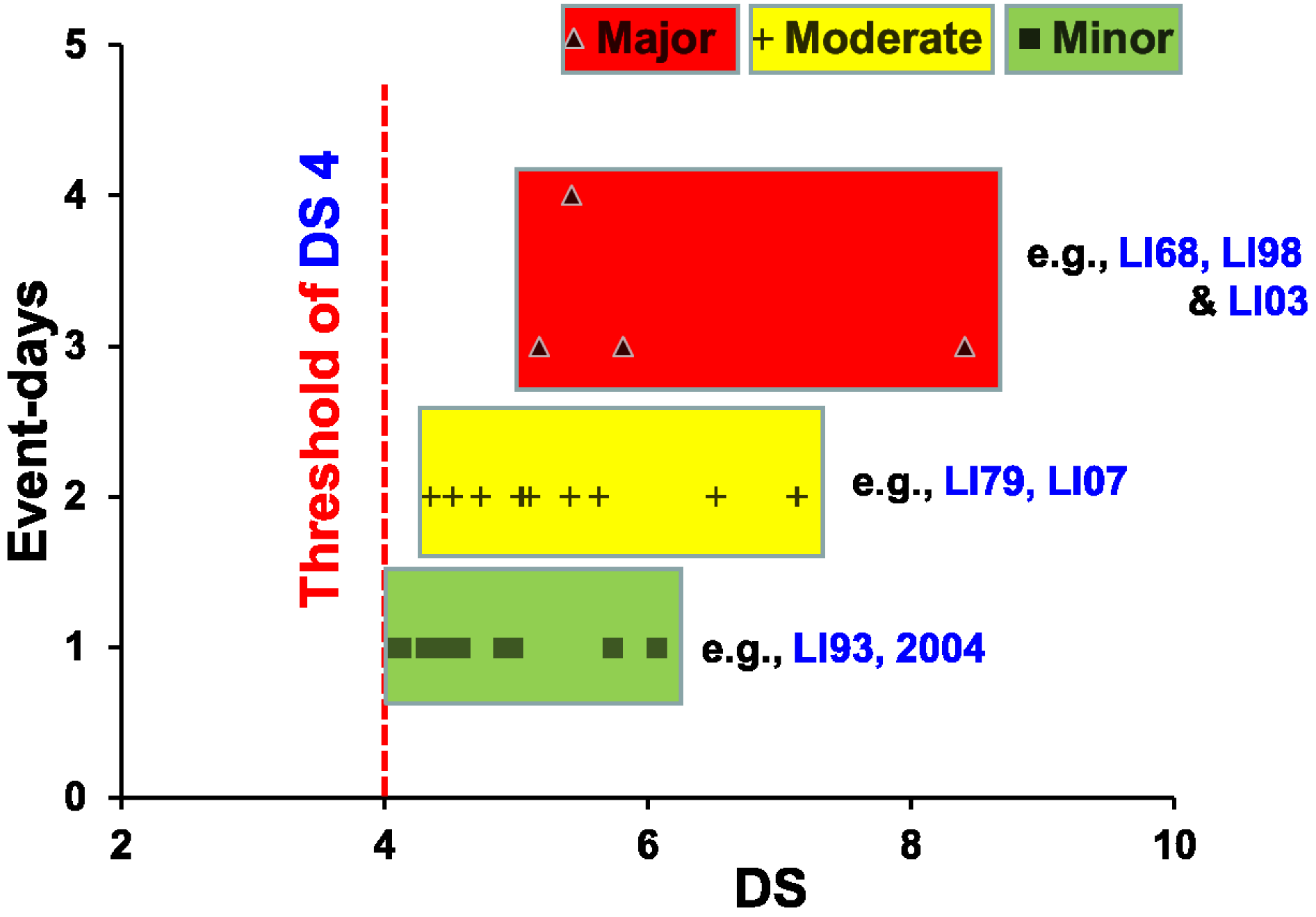
Confirmed landslide days = 24 (1968-2007)

How to classify events based on magnitude

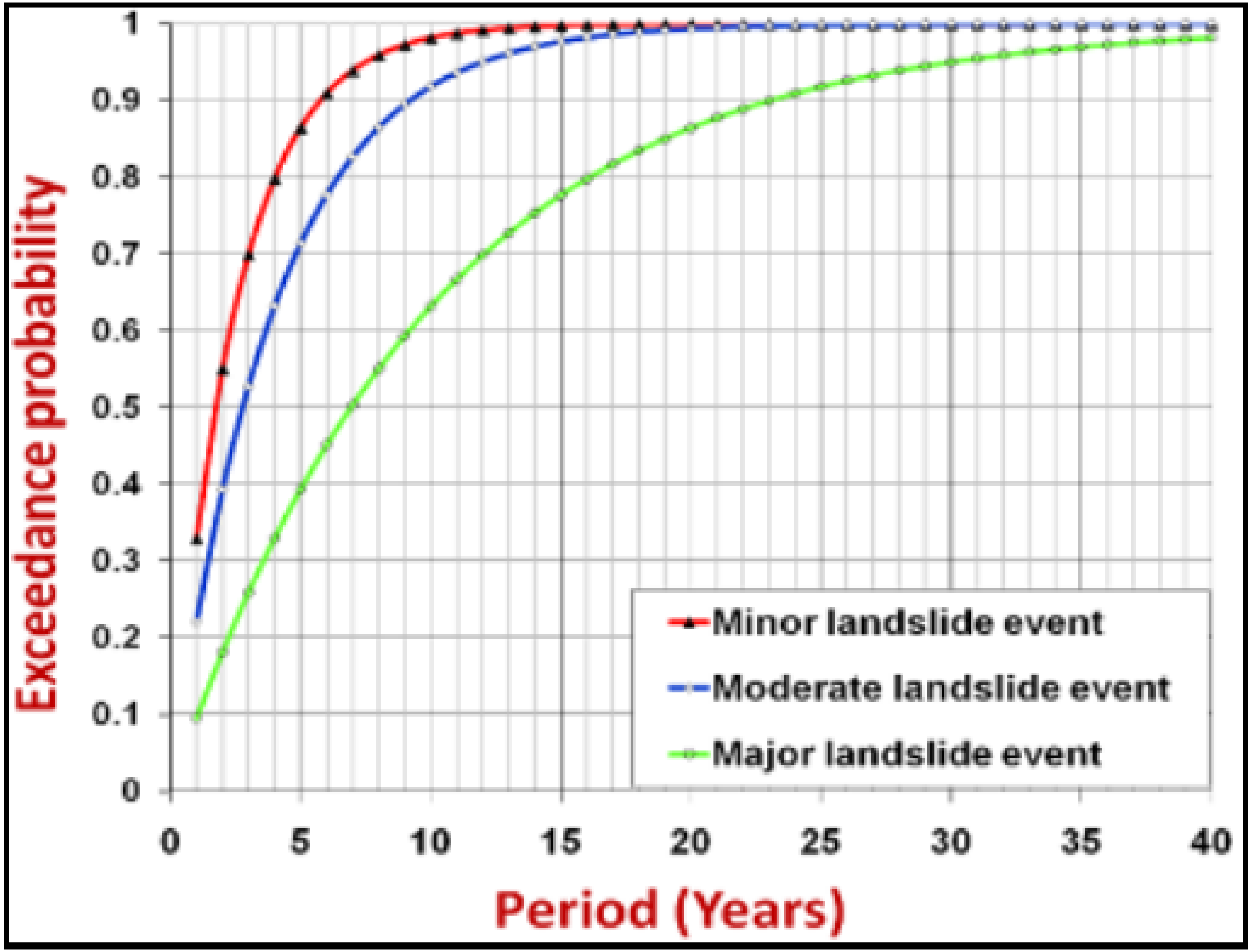
				Predicted		Total
				No landslide	Landslide	
Cases for model calibration	Original	Count (days)	No landslide	4610	232	4842
			Landslide	4	16	20
Cases for model validation	Original	Count (days)	No landslide	1196	58	1254
			Landslide	0	4	4

$$DS = -0.637 + (0.021\,DR) + (0.01\,AR_1) + (0.004\,AR_2) - (0.003\,AR_5)$$

Classification of Events based on Magnitude



Calculation of Probability of Event



$$P[N_L(t) \geq 1] = 1 - P[N_L(t) = 0] = 1 - e^{-\lambda t} = 1 - e^{-t/\mu}$$

Poisson's Distribution Model

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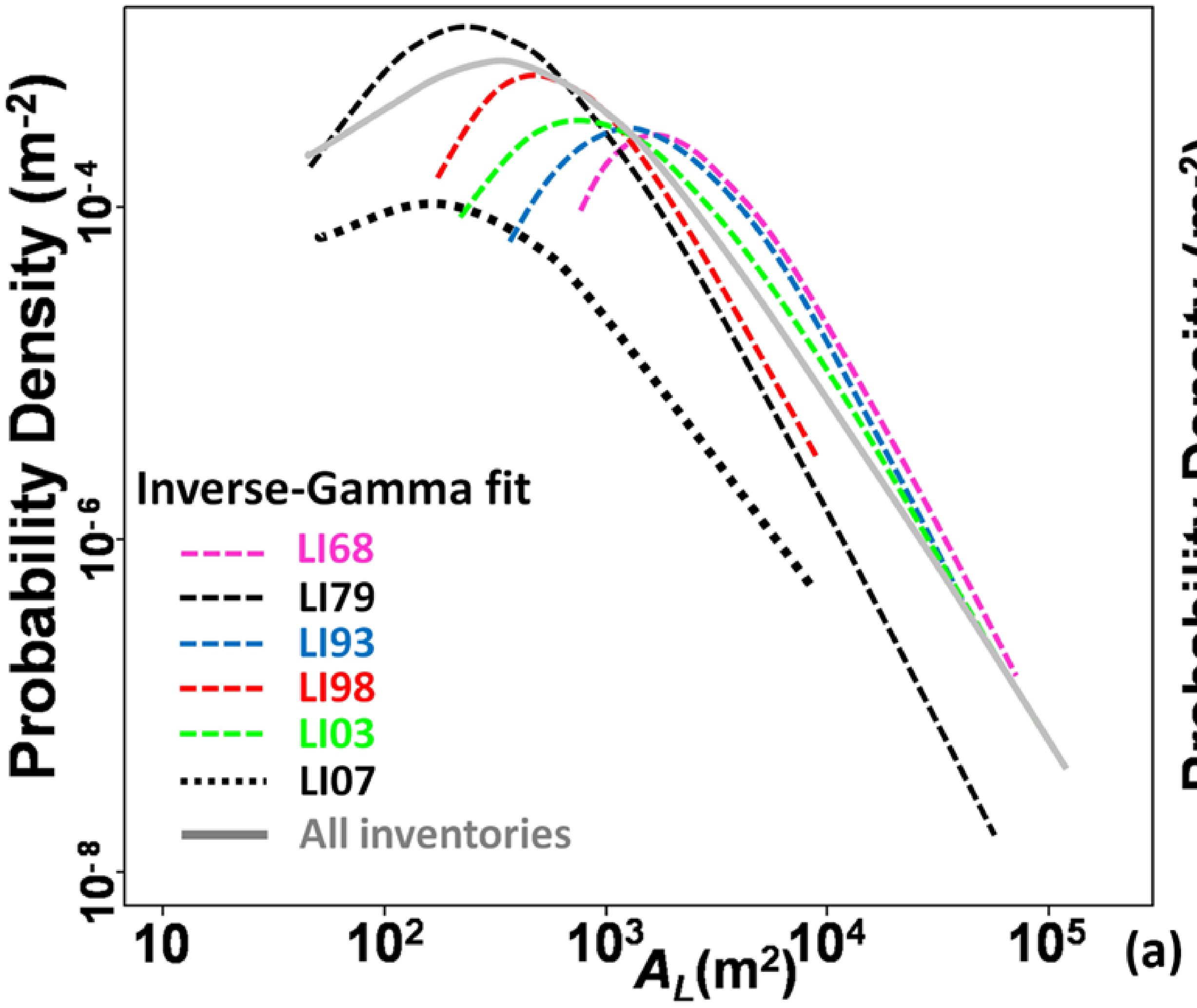
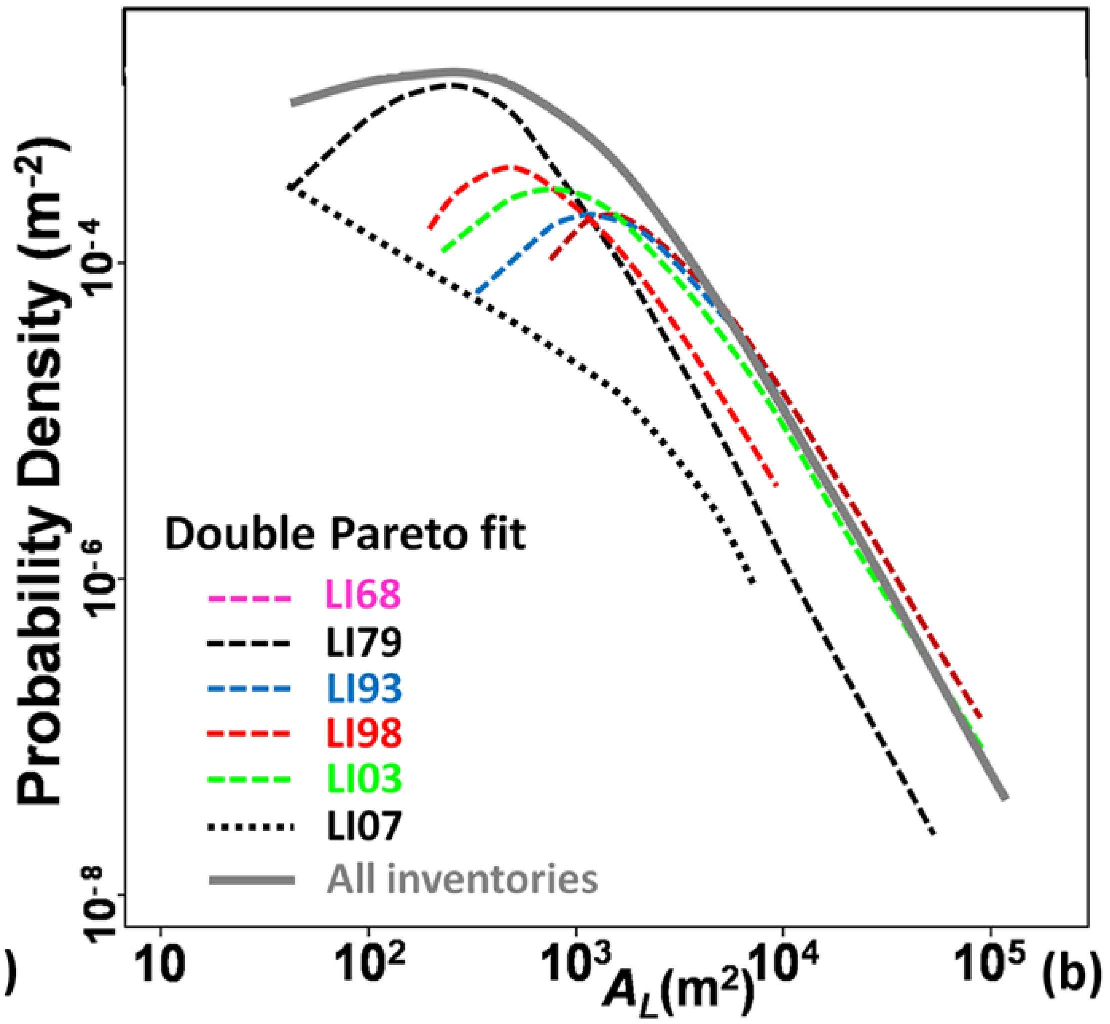
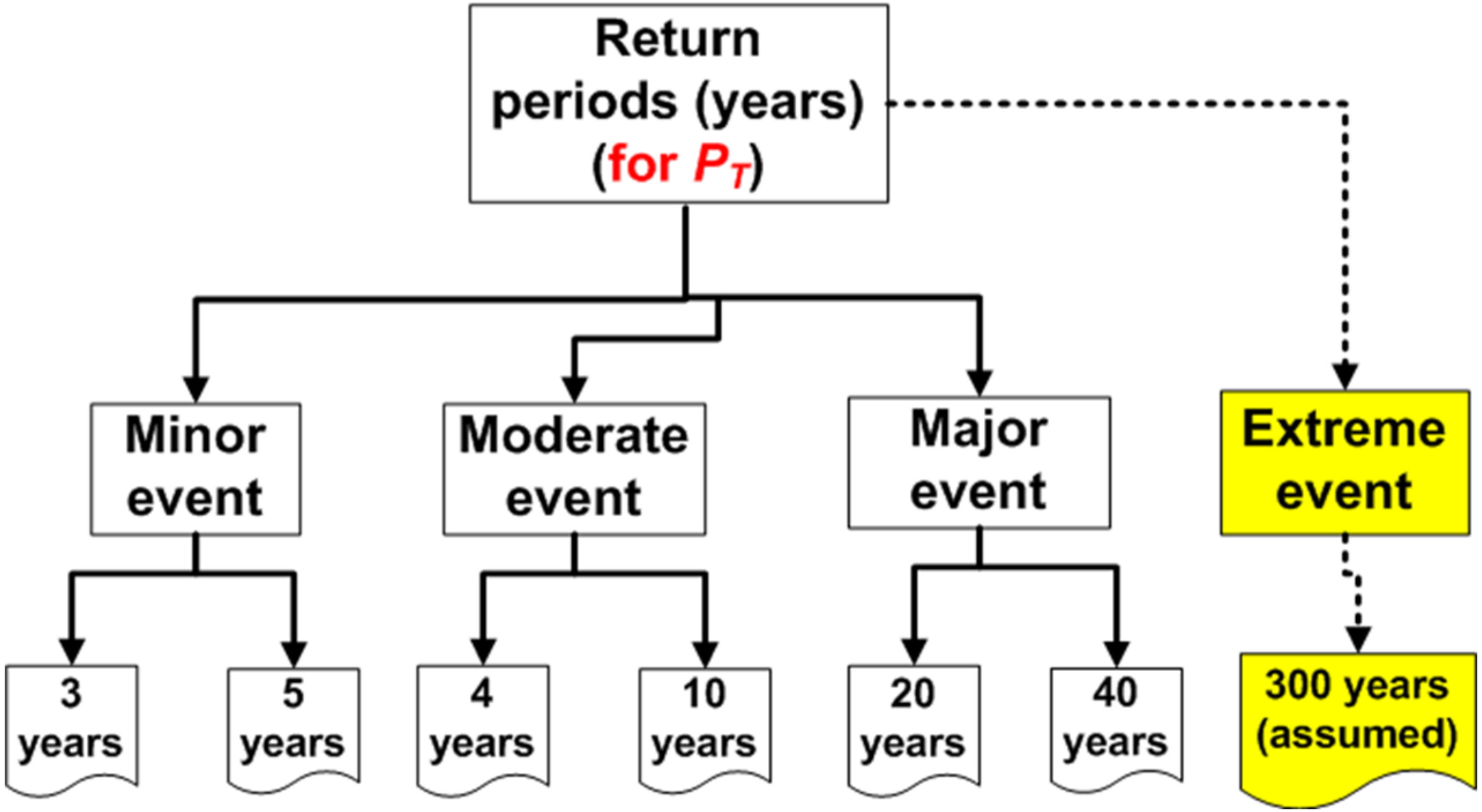
Alternative: Probability of Event based on landslide size





Malamud *et al.*, 2004

Probability (Event) Temporal Prediction



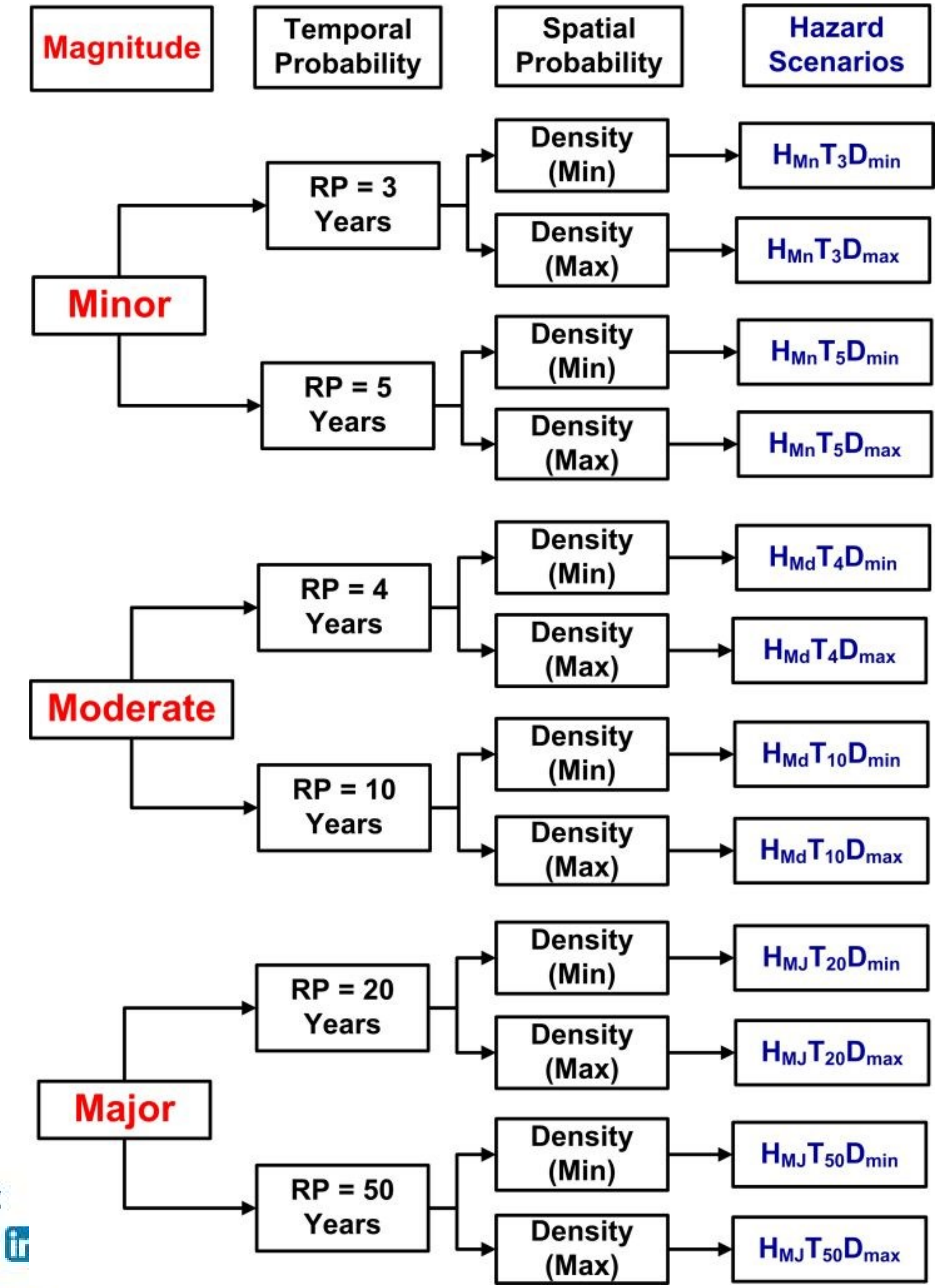
Total predicted events = 30

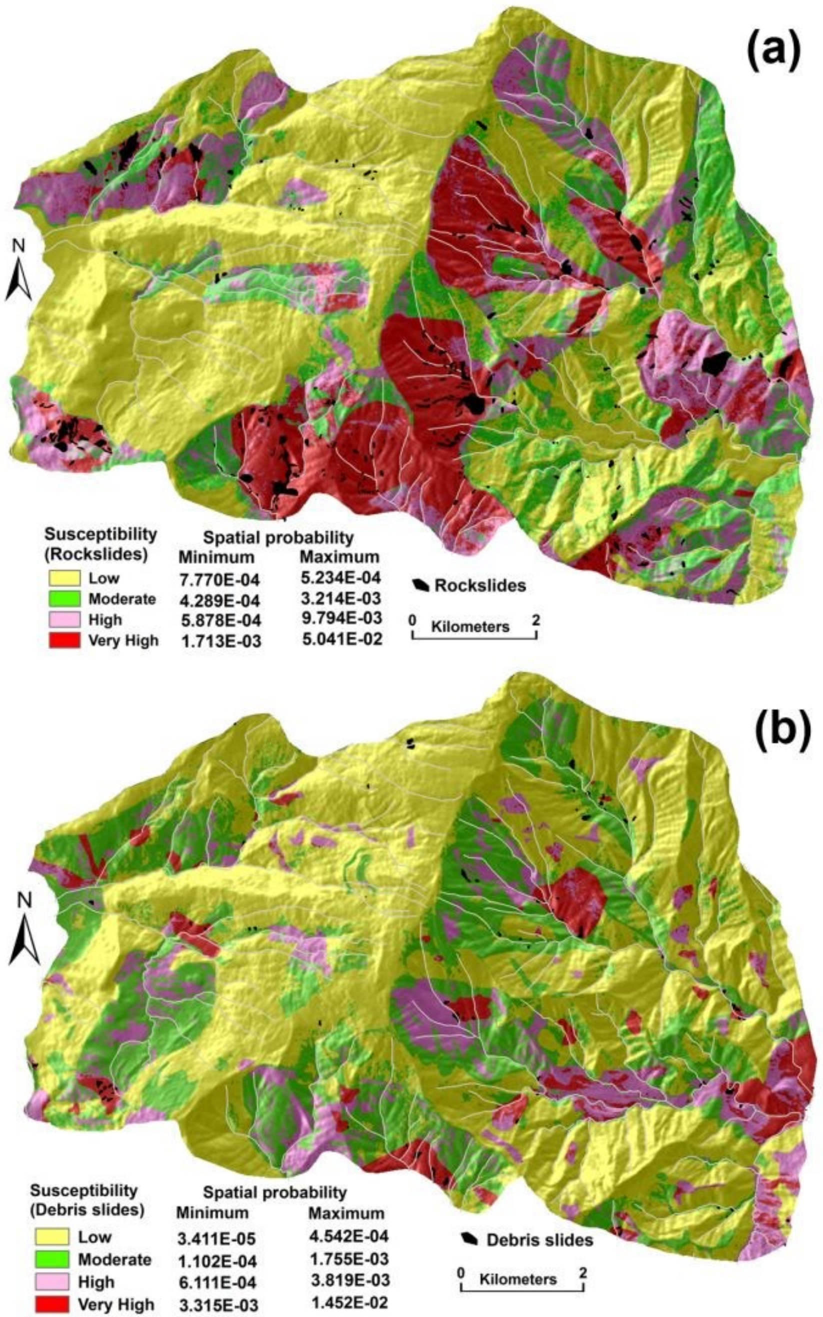
Analysis period = 1968-2007 (40 years)

Major = 4 (2) Moderate = 10 (4) Minor = 16 (8)

Annual probability = 1/ Return period

Hazard Scenarios and Maps





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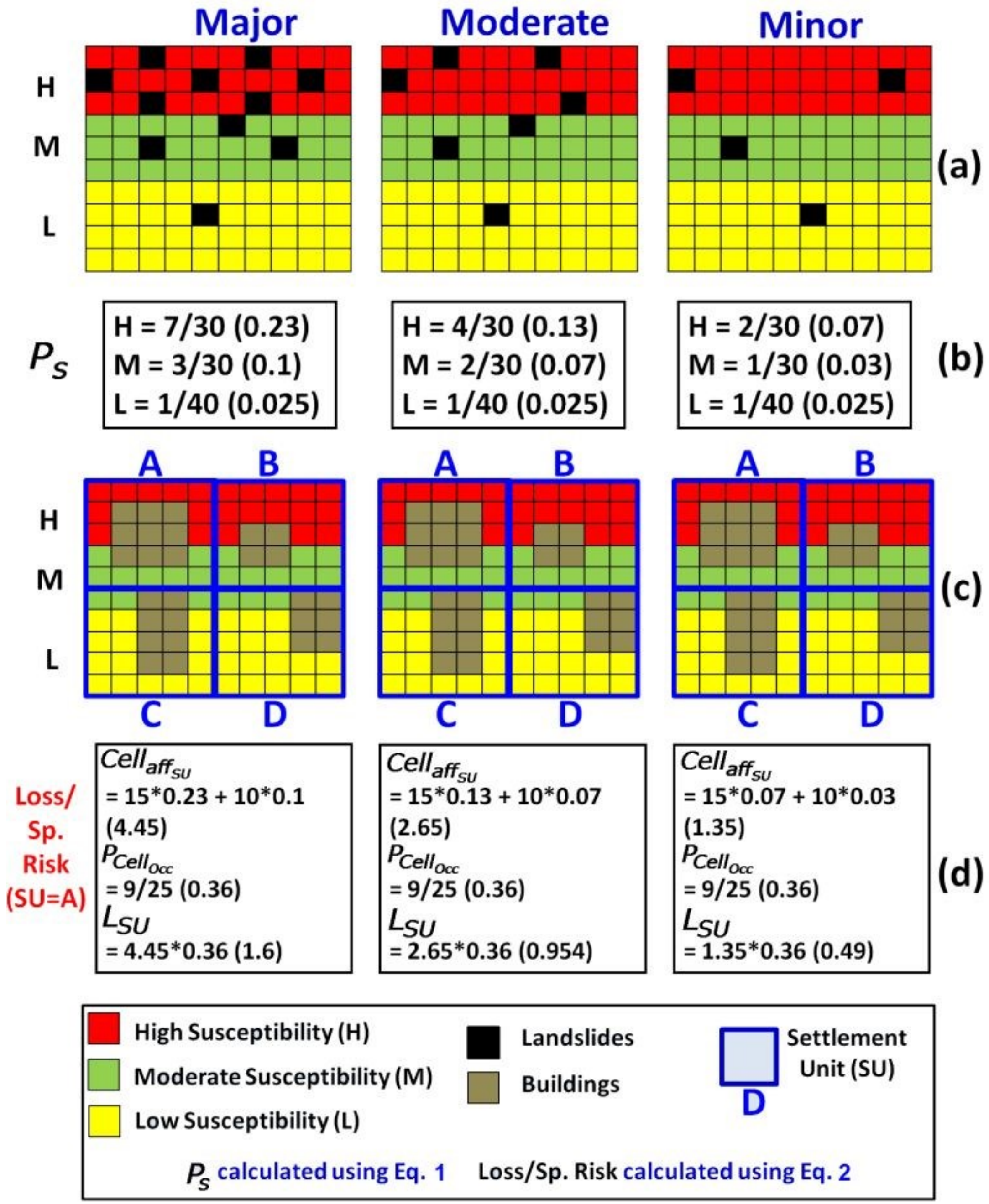
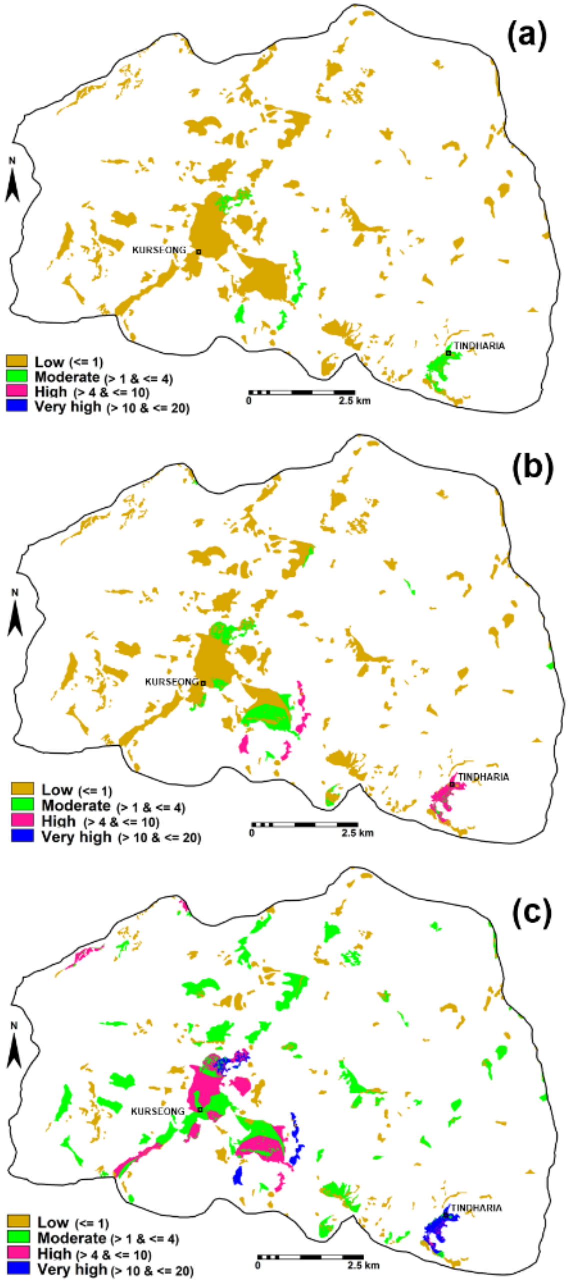
Consequence Analysis and Risk Maps





Minor Losses

Moderate Losses

Major Losses

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Hazard descriptor	Rock falls from natural cliffs or rock cut slope	Slides of cuts and fills on roads or railways	Small landslides on natural slope	Individual landslides on natural slopes
	Number/ annum/km or cliff or rock cut slope	Number/ annum/ km of cut or fill	Number/ km^2/annum	Annual probability of active sliding
Very high	>10	>10	>10	10^{-1}
High	1 to 10	1 to 10	1 to 10	10^{-2}
Moderate	0.1 to 1.0	0.1 to 1.0	0.1 to 1.0	10^{-3} to 10^{-4}
Low	0.01 to 0.1	0.01 to 0.1	0.01 to 0.1	10^{-5}
Very low	<0.01	<0.01	<0.01	$<10^{-6}$

Likelihood	Annual Probability	Consequences to property (with indicative approximate cost of damage)[(1)(3)]				
		1: Catastrophic	2: Major	3: Medium	4: Minor	5: Insignificant
		200%	60%	20%	5%	0.5%
A – Almost Certain	10^{-1}	VH	VH	VH	H	M or L
B-Likely	10^{-2}	VH	VH	H	M	L
C-Possible	10^{-3}	VH	H	M	M	VL
D-Unlikely	10^{-4}	H	M	L	L	VL
E-Rare	10^{-5}	M	L	L	VL	VL
F-Barely credible	10^{-6}	L	VL	VL	VL	VL

Limitations & Constraints

- Incomplete historic landslide inventory data
- Non-availability of landslide dates
- Non-availability of information on landslide dimension (area & volume)
- Poor spatial distribution of rainfall stations
- Non-availability of rainfall intensity information
- Non-availability of up-to-date census information

THANK YOU & Please Stay Safe

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