Operationalising a national programme of landslide susceptibility mapping

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Workshop on “Use of EO Data in Disaster Management…” (8-11 March 2016, NRSC, Hyderabad)
What are landslides???

... the movement of a mass of rock, debris or earth down a slope due to the action of gravity
Landslide in a Tea Garden 1968

Convey Buried October 1968

Anderson (Teesta) bridge, Oct 1968

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

Profuse loss of resources
Society vs. Landslide

- Viewed as an individual problem
- Ignorance/lack of awareness
- Informal/formal settlements in hazardous areas
- Society accept the risk and live with it
- Makes society more vulnerable

How to manage landslide risk?
GSI’s contribution

- Dates back to 1880 (Nainital landslide)
- Pre-disaster studies (for planning & preparedness)
  - 1:50/25k landslide susceptibility mapping
  - 1:10/5k landslide susceptibility mapping
- Post-disaster studies (for planning & remediation)
  - Landslide inventory mapping
  - 1:1/2k landslide mapping & slope stability studies
- Monitoring & Early Warning
- Awareness Programme
- Data management & dissemination
- Research & Development

GSI has been declared by GoI as the Nodal Agency for landslide studies w.e.f. 2004
Lesson learnt from recent events

- 2013 Uttarakhand event; 2014 Malin event; 2015 Darjeeling event

- All hill slopes may not be prone to landslides (initiation or run-out) ???

- Magnitude of triggers largely control landslide type, failure mechanism & distribution

- Many casualties are from new (= one-time) failures

How to reduce landslide risk?
Why NLSM?

- Non-availability of seamless database on landslides
- No Pan-India Landslide Susceptibility Map
- Retrieval and updation difficult with available analog maps
- How to prioritize areas for detailed studies
Objective of NLSM

- To prepare GIS-based seamless Landslide Susceptibility Maps using inputs from RS data and fieldwork.

- Creation of a national repository on Landslide Inventory

- To facilitate easy retrieval, dissemination and updation of landslide susceptibility information

Creation of a dynamic **National Landslide Susceptibility Database** for India
NLSM Target & Challenges

- Launched w.e.f. FS 2014-15
- Target area: 1034 toposheets (0.42 M. sq km)
- Seamless map generation.
- Inaccessibility, steep topography, extreme climate, complicated geomorphic and geodynamic set up
- Different conditions influencing susceptibility
- Different landslide types and movement

- 0.13 M. Sq Km
- 0.18 M. Sq Km
- 0.09 M. Sq Km

- 116 Districts
- 366 Taluks
- 65000 Villages/ Settlements
Training & Capacity Building (GHRM Cell)

A. Brain-storming session
B. Specialised Training Module
C. Interactive Orientation Programmes

82 Officers & 15 Supervisory Officers are now working for NLSM in GSI

(11th May to 12th June 2015)

Geohazards Research & Management (GHRM) Cell
GSI, CHQ, Kolkata

As directed by the Director General, GSI, Geohazards Research & Management (GHRM) Cell, GSI, CHQ, Kolkata organised five interactive orientation programmes at different Regions’ States between 11th May and 12th June 2015 to facilitate smooth initiation and implementation of 36 items of National Landslide Susceptibility Mapping (NLSM) Programmes of GSI (FS 2015-16). The following five interactive orientation programmes were attended by the 61 field and supervisory level officers who are engaged in the on-going NLSM Programmes in five Regions – Eastern, Northeastern, Northern, Southern and Central (Annamalai).
Total NLSM Target = 424.5 (x1000) km²

| Target | Priority 1 |  | Priority 2 |  |
|--------|------------|  |------------|  |
|        | Priority areas with settlement & roads (RS & detailed Field work) |  | Highly inaccessible & high altitude areas (Mainly RS with very limited field checks) |  |
|        | Toposheet | Area (in 1000 km²) | Toposheet | Area (in 1000 km²) |
| NR     | 158       | 75.4            | 207       | 74.5     |
| ER     | 15        | 2.9             | -         | -        |
| NER    | 233       | 109.3           | 167       | 71.2     |
| SR     | 186       | 62.6            | -         | -        |
| CR     | 68        | 28.6            | -         | -        |
| Total  | 660       | 278.8           | 374       | 145.7    |

Priority 1 is presently in progress by GSI w.e.f. FS 2014-15
## NLSM Progress & Perspective Plan (Priority 1)

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>NR</td>
<td>75.3</td>
<td>16.48</td>
<td>11.53</td>
<td>12.39</td>
<td>13.02</td>
<td>13.01</td>
<td>8.86</td>
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<tr>
<td>ER</td>
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<td>0</td>
<td>1.41</td>
<td>1.5</td>
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<td>-</td>
<td>-</td>
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<td>NER</td>
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<td>18.78</td>
<td>21.16</td>
<td>23.12</td>
<td>23.12</td>
<td>23.12</td>
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<td>SR</td>
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<td>14.14</td>
<td>12.18</td>
<td>12.11</td>
<td>12.11</td>
<td>12.11</td>
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<tr>
<td>CR</td>
<td>28.61</td>
<td>0</td>
<td>2.46</td>
<td>4.12</td>
<td>7.34</td>
<td>7.34</td>
<td>7.34</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>278.8</strong></td>
<td><strong>16.48</strong></td>
<td><strong>48.32</strong></td>
<td><strong>51.09</strong></td>
<td><strong>55.59</strong></td>
<td><strong>55.59</strong></td>
<td><strong>51.43</strong></td>
</tr>
</tbody>
</table>

| Cum target  | 16.48 | 64.8 | 116.15 | 171.74 | 227.32 | 278.8 |
| Cum % of target | 6%    | 23%  | 42%    | 62%    | 82%    | 100%  |

- Already completed in FS 2014-15
- Currently under execution in FS 2015-16
- Proposed for FS 2016-17; awaiting approval at CGPB Meeting, February 2016
- Perspective Plan (for FS 2017-18, 18-19 & 19-20)
**Data Preparation**

- Resourcesat-2 LISS-III MX (23.5 m) LISS-IV MX (5.8 m) Google Earth Imagery
- ASTER DEM (30 m)
- Legacy Data & Data from RS inputs such as LISS IV, LISS III & Google Earth Imagery
- Ground data/Checking Fieldwork

1. Landslide Inventory Map
2. Updating of legacy data

1. Slope map
2. Aspect map
3. Curvature

1. 1:50K Geology Map
2. 1:50K Geomorphology and Lineament Map
3. 1:50K Land use/cover map

1. Augmentation of landslide inventory data
2. Ground validation and updating of Legacy & other maps prepared using high-resolution imagery
3. Slope forming material & depth

**Analysis & Modeling**

- Landslide Inventory
- Causative Thematic maps
- Spatial Association Analysis

- Selected & Weighted Predictors
- Weighted Multi-class Index Overlay
- Validation

- Seamless maps in GSI and NRSC Portals
- Landslide Susceptibility Maps
NLSM Modeling in landslide dominant areas (e.g., Himalayas)

Geofactor themes used

Slope
Aspect
Curvature
Land use/ cover
Geomorphology
Slope Forming Material (SFM)
Thickness
Proximity to drainage
Proximity to roads
Proximity to faults/ fractures

&

Landslide inventory maps
NLSM Modeling in landslide deficient areas (e.g., South India)

Rating of geofactors using AHP

- Selected & Weighted factors
- Weighted Multi-class Index Overlays
- Landslide Susceptibility Score Map
- Quantitative validation (success rate)
- Landslide Susceptibility Map

Geofactor themes used

- Slope
- Aspect
- Curvature
- Land use/cover
- Geomorphology
- Slope Forming Material (SFM)
- Depth
- Proximity to drainage
- Proximity to roads
- Proximity to faults/fractures
Processes or steps for each NLSM

I. Preparation of Landslide Spatial Database
II. Preparation of Geofactor Spatial Database
III. Determining Rating and Weight of Geofactors
IV. Integration, validation & predictive modeling of landslide susceptibility
I. Preparation of Landslide Spatial Database

Source: Multiple
Visual Interpretation of high-resolution imagery
Mapping landslides using Multi-temporal RS data of multiple time (2) (Main Source: NRSC)

Digitisation as polygons
Attribute data entry
Using high-resolution imagery of different temporal period
Using high-resolution imagery of different temporal period
Importing the field-based landslide inventory data in GIS
Adding attributes of landslides in GIS (41-point Geoparametric Data Format)
Combining landslide data mapped from different sources
Preparation of landslide data (as points) for analysis & modeling (use of merging...)

- Open ArcMap and open RSpoly.shp
- In Arc Toolbox click and expand Conversion Tools and then To Raster
- Click Polygon to Raster
- Input Feature: add RSPoly
- Value Field: add Id or FID
- Output Raster Dataset: ...
- Right Click raster RSPoly, click Open Attribute Table. Attribute table of RSPoly opened.
- In Arc Toolbox again click and expand Conversion Tools and then From Raster and then click Raster to Point
- Input Raster: RSPoly; Output Point Feature: RSPolypt
- In Arc Toolbox click and expand Data Management Tools and then General then click Merge
- In Merge dialog box add both the datasets RSPolypt and ls_pt
- Output Dataset: ...

merged landslide file lsm.shp is combined landslide Point Data for use in subsequent analysis
Training/ Calibrating and Testing/ Validating Landslide Data
II. Preparation of Geofactor Thematic Maps

Source: Multiple
<table>
<thead>
<tr>
<th>Sl No</th>
<th>Thematic group</th>
<th>Geofactor themes</th>
<th>Thematic classes</th>
<th>Data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Slope morphometry</td>
<td>Slope Gradient</td>
<td>Reclassified as 5 degree intervals</td>
<td>Continuous</td>
</tr>
<tr>
<td>2.</td>
<td>Curvature</td>
<td></td>
<td>Classified into 5 to 6 classes</td>
<td>Categorical</td>
</tr>
<tr>
<td>3.</td>
<td>Aspect</td>
<td></td>
<td>NNE, NE, ENE, ESE, SE, SSE, SSW, SW, WSW, WNW, NW &amp; NNW</td>
<td>Categorical</td>
</tr>
</tbody>
</table>

**Source:** 30 m resolution ASTER DEM or 10 m resolution CartoDEM after getting the layers from NRSC
<table>
<thead>
<tr>
<th>4.</th>
<th>Geomorphology</th>
<th>Geomorphology (Base 1:50K NGLM layer to be provided by GHRM Cell; Data for Target areas of FS 2014-15 already procured)</th>
<th>Colluvial fan, Alluvial fan, Alluvial plain, Intermontane plateau, Lowly dissected valley, Moderately dissected valley, Highly dissected valley, Ridge and spur, Old river terrace, Denudational valley and niche, Steep escarpments, etc.</th>
<th>Categorical</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>Slope forming material</td>
<td>Material (1:50K Geology map already procured to be provided by GHRM Cell)</td>
<td>Scree, Regolith, Lithomarge, Laterite, Alluvium mixed with colluvium, Colluvium, Talus, Alluvium, Older well compacted debris, Younger loose debris material, Different rock types (Fresh), Different rock types (weathered) ... etc.</td>
<td>Categorical</td>
</tr>
<tr>
<td></td>
<td>Slope forming material</td>
<td>Thickness</td>
<td>Categorical</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>------------------------</td>
<td>-----------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0 - 1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 1 m &amp; &lt;= 5 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 5 m &amp; &lt;= 10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 10 m &amp; &lt;= 20 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 20 m</td>
<td>Categorical</td>
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<table>
<thead>
<tr>
<th>7</th>
<th>Structure</th>
<th>Fault/ Fracture</th>
<th>Distance to Fault/ Fracture</th>
<th>Continuous or Categorical</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Regional Thrust/ Shear</td>
<td>Distance to Regional Thrust/ Shear</td>
<td>Continuous or Categorical</td>
<td></td>
</tr>
</tbody>
</table>
### Land use/cover

<table>
<thead>
<tr>
<th>Land use/cover</th>
<th>Land use/cover types</th>
<th>Barren, Agricultural land Plantation, Settlement Moderately vegetated forest, Thick forest, Sparsely vegetated forest ... etc.</th>
<th>Categorical</th>
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</thead>
<tbody>
<tr>
<td>Major roads</td>
<td>Distance to road</td>
<td>Continuous or Categorical</td>
<td></td>
</tr>
<tr>
<td>Geo-hydrology</td>
<td>Drainage</td>
<td>Distance to Drainage</td>
<td>Continuous or Categorical</td>
</tr>
</tbody>
</table>

LU LC pre-field maps can be prepared using Toposheet/ available satellite imagery, Google Earth Data through visual interpretation only
DEM Data

5. Select “Spatial Analyst Tool” from the Toolbox Menu
6. Then expand it by clicking the “+” button on the left of the “Spatial Analyst Tool”
7. Further expand “Surface” in the similar manner within expanded “Spatial Analyst Tool”
8. Click “Slope” tool within “Surface”
Slope

- **Layers**
  - **slope**
    - **Value**
      - High: 69.5081
      - Low: 0
    - **DEMs.img**
      - **Value**
        - High: 2621
        - Low: 67
Aspect
Curvature

Value
High: 19.1111
Low: -20.1111
Prepared using Slope, Geomorphology, LU LC, Geology maps as Proxies.
Pre-field Thickness Map
Pre-field Geomorphology Map
Updating Fault/Fracture Map

Hillshade Map In Background
Geofactor Spatial Database

Landslide Spatial Database

Training

Testing
III. Determination of Rating & Weights
Conceptual Model

- Slide Type - 1
  - Factor-1 (Continuous)
  - Factor-2 (Categorical)
  - Factor-3 (Categorical)
  - Factor-4 (Cont)
  - Factor-5 (Categ.)

- Class - X
- Class - Y
- Value >= ?
- Class - M or Class - N
- Class - A
- Class - B

- Value >= c1
- C2=<value<c1
- C3=<value<c2
Yule’s Co-efficient
(Yule, 1912; Fleiss, 1991; Bonham-Carter, 1994)

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

\[
\begin{align*}
T \cap O &= T_{11} = 345 \\
I \cap O &= T_{21} = 141 \\
\bar{I} \cap O &= T_{12} = 382 \\
\bar{I} \cap \bar{O} &= T_{22} = 2077
\end{align*}
\]

- \( T_{11} \) → derived from cross operation
- \( T_{12} = O - T_{11} \)
- \( T_{21} = I - T_{11} \)
- \( T_{22} = T - T_{11} - T_{12} - T_{21} \)

Note: an example of \( I \) is a slope aspect class
Which Geomorphology classes have positive spatial association with landslides
### Analysis Table

**Histogram Table of Geomorphology Theme (NpixC)**

<table>
<thead>
<tr>
<th>NpixC</th>
<th>NpixT</th>
<th>T11</th>
<th>T21</th>
<th>T12</th>
<th>T22</th>
<th>Yc</th>
<th>LOFS</th>
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<tbody>
<tr>
<td>Active Flood Plain</td>
<td>227078</td>
<td>764281</td>
<td>27</td>
<td>227032</td>
<td>7787</td>
<td>7760</td>
<td>529443</td>
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<tr>
<td>Highly Dissected Hills and Valleys</td>
<td>222887</td>
<td>764281</td>
<td>3170</td>
<td>219717</td>
<td>7787</td>
<td>4761</td>
<td>536777</td>
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<tr>
<td>Landslide</td>
<td>905</td>
<td>764281</td>
<td>29</td>
<td>876</td>
<td>7787</td>
<td>7758</td>
<td>755513</td>
</tr>
<tr>
<td>Lowly Dissected Hills and Valleys</td>
<td>115470</td>
<td>764281</td>
<td>1716</td>
<td>113754</td>
<td>7787</td>
<td>6071</td>
<td>642740</td>
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<tr>
<td>Moderately Dissected Hills and Valleys</td>
<td>141876</td>
<td>764281</td>
<td>2574</td>
<td>139302</td>
<td>7787</td>
<td>5213</td>
<td>617192</td>
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<tr>
<td>Older Flood Plain</td>
<td>18936</td>
<td>764281</td>
<td>5</td>
<td>18931</td>
<td>7787</td>
<td>7782</td>
<td>713763</td>
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<tr>
<td>River</td>
<td>37129</td>
<td>764281</td>
<td>266</td>
<td>36863</td>
<td>7787</td>
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<td>719631</td>
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<tr>
<td>Min</td>
<td>905</td>
<td>764281</td>
<td>5</td>
<td>876</td>
<td>7787</td>
<td>7782</td>
<td>755513</td>
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<tr>
<td>Max</td>
<td>227078</td>
<td>764281</td>
<td>3170</td>
<td>227032</td>
<td>7787</td>
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<td>755513</td>
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<tr>
<td>Avg</td>
<td>109183</td>
<td>764281</td>
<td>1112</td>
<td>108071</td>
<td>7787</td>
<td>6675</td>
<td>698423</td>
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<tr>
<td>Std</td>
<td>93983</td>
<td>0</td>
<td>1356</td>
<td>93217</td>
<td>0</td>
<td>1356</td>
<td>93217</td>
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<tr>
<td>Sum</td>
<td>764281</td>
<td>5349967</td>
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<td>756494</td>
<td>54509</td>
<td>46722</td>
<td>4538964</td>
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\[
Y_c = \frac{\sqrt{T11/T21} - \sqrt{T12/T22}}{\sqrt{T11/T21} + \sqrt{T12/T22}}
\]
# Inter-predictor Weights

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<tbody>
<tr>
<td>Theme</td>
<td>MinYC/MinDiff</td>
<td>Max YC/ MaX Diff</td>
<td>Index</td>
<td>Weight</td>
<td>IntWt</td>
</tr>
<tr>
<td>2 Material</td>
<td>-0.831</td>
<td>0.461</td>
<td>1.292</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>3 Geom</td>
<td>-0.835</td>
<td>0.285</td>
<td>1.12</td>
<td>0.9</td>
<td>9</td>
</tr>
<tr>
<td>4 Slope</td>
<td>0</td>
<td>0.35</td>
<td>0.35</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>5 Aspect</td>
<td>-0.087</td>
<td>0.132</td>
<td>0.219</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>6 Depth</td>
<td>-0.824</td>
<td>0.247</td>
<td>1.071</td>
<td>0.8</td>
<td>8</td>
</tr>
<tr>
<td>7 Curvature</td>
<td>-0.113</td>
<td>0.201</td>
<td>0.314</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>8 Dist_Drainage</td>
<td>0</td>
<td>0.23</td>
<td>0.23</td>
<td>0.2</td>
<td>2</td>
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<tr>
<td>9 Dist_Shear</td>
<td>-0.01</td>
<td>0.19</td>
<td>0.2</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>10 Dist_Road</td>
<td>0</td>
<td>0.12</td>
<td>0.12</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>11 Dist_Frac</td>
<td>0</td>
<td>0.09</td>
<td>0.09</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
</tr>
</tbody>
</table>
IV. Integration, Validation & Creation of Susceptibility Maps
Weighted Multi-class Index Overlay

\[
\bar{S} = \frac{\sum_i^n (LOFS_{i\text{ii}} \times W_i)}{\sum_i^n W_i}
\]

\[
\text{Susc} = \frac{(10 \times \text{LOFS\_mat} + 9 \times \text{LOFS\_Geom} + 3 \times \text{LOFS\_Slope} + 2 \times \text{LOFS\_Asp} + 8 \times \text{LOFS\_Depth} + 2 \times \text{LOFS\_curv} + 2 \times \text{LOFS\_Dr} + 2 \times \text{LOFS\_SH} + 1 \times \text{LOFS\_Rd} + 1 \times \text{LOFS\_frac})}{39}
\]
Susceptibility Score Map
Validation

Susceptibility Score Map

Cross or Overlay
<table>
<thead>
<tr>
<th>Susc</th>
<th>npixc</th>
<th>npixcc</th>
<th>npixt</th>
<th>Propcc</th>
<th>npixls</th>
<th>npixlsc</th>
<th>npixs</th>
<th>Success</th>
</tr>
</thead>
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<tr>
<td>0.85</td>
<td>70876</td>
<td>70876</td>
<td>760000</td>
<td>0.09</td>
<td>1892</td>
<td>1892</td>
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<td>0.24</td>
</tr>
<tr>
<td>0.46</td>
<td>69873</td>
<td>140749</td>
<td>760000</td>
<td>0.19</td>
<td>1364</td>
<td>3256</td>
<td>7782</td>
<td>0.42</td>
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<tr>
<td>0.43</td>
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Min: 60801  Max: 89599  Avg: 76000  StD: 411807  Sum: 760000

Success & Prediction Rate Curves (Chung & Fabbri, 1999)
Classification to prepare qualitative landslide susceptibility map
Final landslide susceptibility map
Landslide hazard

- 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 hazard Analysis

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

Landslide Susceptibility Analysis/ Mapping (LSA/ LSM)

- To predict/ determine the spatial locations of future landslides… a pre-requisite for hazard analysis
Regional landslide hazard mitigation: A Way Forward

- Identify the most appropriate geofactors for multi-scale landslide susceptibility analysis
- Identify landslide susceptibility scenarios based on landslide failure mechanisms, magnitudes and triggers.
- Developing methodologies to convert landslide susceptibility maps into true hazard and risk maps in a data-scarce environment.
- Developing Regional Early Warning System (EWS) for landslide hazards using InSAR and through threshold modeling of climatic triggers
- Quantifying the effect and extent of landslide susceptibility owing to rapid land use changes.
Site-specific landslide hazard mitigation: A Way Forward

- Deterministic slope stability modeling aiming at to model variable hydrologic situations
- Long-term instrument-aided monitoring and development of thresholds
- Designing relevant retaining structures based on different slope stability conditions and scenarios
- Rockfall stability modeling and designing the relevant rockfall retaining structures