Glaciers and Glacial Lake hazard assessment in the transboundary Kailash Sacred Landscape

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Outline

• Background
• Glaciers in KSL
  • Mapping method and Results
• Glacial Lake hazard assessments
  • Method and Results
• Conclusion and Way Forward
The Hindu Kush Himalaya Region

HKH area: 4.19 million km²

- ~9% of glaciers in globe
- **240 million people** depend directly on HKH for their lives and livelihood
- **1.9 billion people depend** on the HKH for water, Food and Energy
- **>30% of world population** benefits indirectly from HKH resources and ecosystem

- It is the source of countless perennial rivers that originate from glaciers.
- It is also the source of various natural disasters such as snow avalanche, glacial lake outburst floods (GLOF).
Background

1956 photograph of Imja glacier (Photo: Fritz Muller; courtesy of Jack Ives)

2006 photograph of Imja glacier (Photo: Giovanni Kappenberger courtesy of Alton C Byers)

Safer limits of global warming to 1.5°C is even Too HOT for the HKH

The HKH is warming more compared to global mean

Elevation dependent warming

Increase glacier recession and increase in number and area of glacial lakes; increase of Glacial Lake Outburst Floods (GLOFs) risk

In a 1.5°C world, glaciers in the HKH will lose 1/3 of their volume by 2100 and 2/3 of their volume under current emission trends

Snow covered areas and snow volumes will decrease and snowline elevations will rise;

Snow melt induced run-off peak will be stronger and occur earlier in the year
Kailash Sacred Landscape

The landscape covers 31,000 km$^2$ area and located in the central and western Himalayas spanning parts of China, India, and Nepal.

Renowned for the sacred Mount Kailash (6638 masl)

Religious and Spiritual Values – Mount Kailash and Mansarover lake – Buddhism, Hinduism, Bon-Po, Jainism

Three major gigantic river basin of HKH starts from four sides of the Kailash region

Glacier and Glacial lakes are essential element of the multi-cultural and fragile cultural landscape.

Altitudinal variation ranges from 400 – 7700 masl.
Glaciers in KSL

Large perennial ice mass originates on land by recrystallization of snow and other forms of solid precipitation that is moving slowly.

Area larger than or equal to 0.02 km². Scale 1: 50,000

Consistent and homogenous remote sensing data source and methods

Mapping guidelines based on World glacier inventory, Global Land Ice Measurement from Space (GLIMS) and GlobGlacier consortium
Methodology

Training
On-the-Job Training
Supervision and Technical support

Consistent data source
Spatial resolution
Temporal resolution
Accuracy and Quality

Images used – 40 Landsat Tiles
Glacier Status in KSL (2020)

- Glacier area covered *3.8%* of the total landscape area.
- Almost *13.3%* of glaciers are debris covered.
- Milam glacier lies in Kali River is the largest glacier, which covers an area of **49.5 km²**.
- Majority (77%) of glaciers are of size less than 0.5 km² which covers only 18.5% of total glacier area.
- One third of total glacier area is covered by glacier size of 1 to 5km².

<table>
<thead>
<tr>
<th>Basin</th>
<th>Sub-Basin</th>
<th>Glacier Number</th>
<th>Area (km²)</th>
<th>Largest</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>CI</td>
<td>DC</td>
<td>Total</td>
</tr>
<tr>
<td>Ghaghara</td>
<td>Kali</td>
<td>751</td>
<td>57</td>
<td>751</td>
</tr>
<tr>
<td></td>
<td>Humla-Karnali</td>
<td>739</td>
<td>42</td>
<td>739</td>
</tr>
<tr>
<td></td>
<td>West Seti</td>
<td>282</td>
<td>13</td>
<td>282</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1772</td>
<td>112</td>
<td>1772</td>
</tr>
<tr>
<td>Manasarover</td>
<td>169</td>
<td>0</td>
<td>0</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1941</td>
<td>112</td>
<td>1941</td>
</tr>
</tbody>
</table>

*Glacier area covered 3.8% of the total landscape area.*

*Almost 13.3% of glaciers are debris covered.*

*Milam glacier lies in Kali River is the largest glacier, which covers an area of 49.5 km².*

*Majority (77%) of glaciers are of size less than 0.5 km² which covers only 18.5% of total glacier area.*

*One third of total glacier area is covered by glacier size of 1 to 5km².*

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**Elevation (masl)**

- From 3,500 masl to 7,650 masl.
Decadal change (1990 - 2020)

Glacier number has increased by 7.8% (fragmentation)

Glacier area has decreased by 25.5%

Drastic decrease in recent decades, i.e. 2010-2020 (11.9%)

Area percentage of debris-covered (DC) glaciers has increased from 8.7% to 13.3%.

Clean-Ice (CI) glaciers decreased from 91% to 87% from 1990 to 2020
Decadal change (1990 - 2020)

- Shrinkage of larger glaciers led to fragmentation into smaller glaciers.
- Area of all glacier size decreased in each decade with higher area decreased in larger sized glaciers.
- Maximum glacier area loss (33%) was in class 4 and glaciers larger than 10 km$^2$ (class 5) showed 25% loss in 30 years.
- The largest glacier also decreased by more than 9% (54.5 km$^2$ in 1990 to 49.5 km$^2$ in 2020).

- Maximum glacier area loss is at an elevation range from 5,000 to 5,500 masl – ranges 20 -40% in each 100m elevation band.
- Less than 20% area loss in 100 elevation band between 5,500 to 7,000 masl.
- Decreased area below 4,000 masl indicated the retreat of the glacier terminus and upward shifting of glacier elevation.
- The lowest elevation glacier is highly sensitive to temperature, thereby influencing higher rates of ablations.
Glacial Lake and hazard assessment

- Glacial melt water dammed by – Ice, moraine(debris), bedrock, landslide or alluvial fan
- Area $\geq 0.003 \text{ km}^2$ (at least 3-4 pixels in 30m resolution satellite image)
- **737 glacial lakes** covering **31.2\text{km}^2**. (Largest Glacial lake $1.9\text{km}^2$)
- **65%** of glacial lakes are in **Humla-Karnali** (498) followed by Mansarovar (125), Kali (63) and West Seti (51).
- Elevation ranges **3400 - 6100 masl** (90% above 4500 masl)
- More than 45% of GL covering 51% of total lake area are in elevation ranges of 5000 to 5500 masl
- **65 %** are moraine dammed – **13%** end-moraine dam contribute higher area coverage than others.
GLOFs and other disaster around KSL

- 11 GLOFs have been recorded from 6 glacial lakes within KSL
- Six outburst event from supraglacial lake in Halji (2004 – 2011)

<table>
<thead>
<tr>
<th>SN</th>
<th>Year</th>
<th>Location</th>
<th>Elevation</th>
<th>Lake type</th>
<th>River Basin</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>GL081295E30029N</td>
<td>5136</td>
<td>Moraine dammed</td>
<td>West Seti</td>
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<tr>
<td>2</td>
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<td>Humla</td>
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<td>4</td>
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<td>Humla</td>
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<td>5</td>
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<td>GL081664E30164N</td>
<td>4907</td>
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<td>Humla</td>
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<td>6</td>
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<td>5347</td>
<td>Supraglacial</td>
<td>Humla</td>
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<tr>
<td>7</td>
<td>2006</td>
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<td>Humla</td>
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<td>8</td>
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<td>Humla</td>
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<td>2009</td>
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<td>Humla</td>
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<tr>
<td>11</td>
<td>2011</td>
<td>Halji</td>
<td>5347</td>
<td>Supraglacial</td>
<td>Humla</td>
</tr>
<tr>
<td>12</td>
<td>NA</td>
<td>GL081578E29898N</td>
<td>3581</td>
<td>Moraine dammed</td>
<td>Humla</td>
</tr>
</tbody>
</table>

Sources: Zheng et al., 2021; Kropacek et al., 2015; ICIMOD, 2021
Methodology

- Total number: 1080
- Size ranges: 1.1 to 155 km² except two catchments
- Average size: 28.6 km²

**Normalization**
- Lake Density
- Avg. GL area
- GL area change
- Moraine dam GL percent
- Glacier area change
- Max. Potential Peak Flood Discharge

- Weightage calculation of each thematic layer using Analytic Hierarchy Process (AHP)
- Aggregate thematic layers into potential hazard catchments (using Weighted Overlay Method)
- Define hazard potential catchments (Low, Moderate, High, V.High)
Glacial lake size and density

<table>
<thead>
<tr>
<th>Area size class (km²)</th>
<th>Number</th>
<th>Area</th>
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<tbody>
<tr>
<td>Class 1 (&lt;0.02)</td>
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</tr>
<tr>
<td>Class 2 (0.02 - 0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3 (0.05 - 0.1)</td>
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<td></td>
</tr>
<tr>
<td>Class 4 (0.1 - 0.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 5 (0.5 - 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 6 (1 - 5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Kali
- Karnali
- Mansarovar
- West Seti

Glacial lake density

- Kali
- Karnali
- Mansarovar
- West Seti

Glacial lake number vs. basin

- Kali
- Karnali
- Mansarovar
- West Seti
Glacial lake density

Kali: 50.79%
Karnali: 45.38%
Mansarover: 28.80%
West Seti: 54.90%

Moraine dammed lake percentage

Total Moraine dammed lake number
Total glacial lake number

Moraine dammed percentage

Total glacial lake number

Glacial lake type

Kali: 50.79%
Karnali: 45.38%
Humla: 28.80%
Mansarover: 54.90%
West Seti: 0%
Glaciers and glacial lake area changes (2000 – 2015)

- Kali Basin: Area decrease of 0.326 km²
- Karnali Basin: Area decrease of 2.377 km²
- Manasarover Basin: Area decrease of 0.276 km²
- West Seti Basin: Area decrease of 0.397 km²
Peak flood discharge estimation

Maximum possible Discharge from glacial lake (Huggel et al. 2002)

\[ Q_{\text{max}} = 0.00077V^{1.017} \]

where, \( Q_{\text{max}} \) is discharge \( m^3 \) per second

Peak flood discharge in downstream (Chi et al. 2012; Fan et al. 2012)

\[ Q_{\text{pl}} = \frac{V}{Q_p + \frac{L}{v_k}} \]

\( Q_{\text{pl}} \): Flood peak discharge \( m^3 / s \)

\( V \): Volume of the lake, \( m^3 \)

\( Q_p \): Peak discharge at the breach, \( m^3 / s \)

\( L \): Distance from the glacial lake dam, m;

\( v_k \) is an empirical coefficient equal to 3.13 for rivers on plains, 7.15 for mountain rivers and 4.76 for rivers flowing through terrain with intermediate relief, which here we set the value as 7.15.
Maximum potential flood discharge ($m^3/s$)
Weightage calculation

Pairwise comparison matrix and weightage value (AHP)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>GL Density</th>
<th>GL size</th>
<th>GL type percent</th>
<th>GLC Percent</th>
<th>GrC. percent</th>
<th>QP</th>
<th>Wt. value</th>
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</thead>
<tbody>
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<td>GL Density</td>
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<td>0.50</td>
<td>0.25</td>
<td>1.00</td>
<td>3.00</td>
<td>3.0</td>
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<td>GL size</td>
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<td>1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>4.00</td>
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<td>0.18</td>
</tr>
<tr>
<td>GL type percent</td>
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<td>2.00</td>
<td>1.00</td>
<td>2.00</td>
<td>5.00</td>
<td>5.0</td>
<td>0.35</td>
</tr>
<tr>
<td>GLC Percent</td>
<td>1.00</td>
<td>2.00</td>
<td>0.50</td>
<td>1.00</td>
<td>4.00</td>
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<tr>
<td>GrC. percent</td>
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<td>0.25</td>
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<td>QP</td>
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<td>0.33</td>
<td>0.20</td>
<td>0.25</td>
<td>3.00</td>
<td>1.00</td>
<td>0.07</td>
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</tbody>
</table>

Weightage calculation of each thematic layer using Analytic Hierarchy Process (AHP)

Aggregate thematic layers into potential hazard catchments (using Weighted Overlay Method)

Define hazard potential catchments (Low, Moderate, High, V-High)
Final Hazard

**Legend**
- Glacial lakes
- Glaciers
- Stream network
- Basin boundary

**Final Hazard**
- VERY LOW (0.0 - 0.2)
- LOW (0.2 - 0.4)
- MODERATE (0.4 - 0.6)
- HIGH (0.6 - 0.8)

<table>
<thead>
<tr>
<th>River</th>
<th>VERY LOW</th>
<th>LOW (0.2 - 0.4)</th>
<th>MODERATE (0.4 - 0.6)</th>
<th>HIGH (0.6 - 0.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kali</td>
<td>6</td>
<td>11</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Karnali</td>
<td>157</td>
<td>37</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>Mansarover</td>
<td>42</td>
<td>7</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>West Seti</td>
<td>49</td>
<td>6</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion and way forward

- Significant decreases in glacier area accompanied by an increase in number of glaciers is clear evidence of fragmentation because of uneven shrinkage of individual glaciers.

- Distribution of glacier area and its retreat amount was higher at elevation range from 5,000 – 5,500 masl.

- Moreover, glaciers in the steep slopes, facing the southern aspect and frontal parts of the glaciers associated with glacial lakes are retreating faster.

- The trend of retreat will continue with warming climate and increases the formation and expansion of glacial lake that will increase risk of GLOF

- Present trend in glacier melt enhance economic opportunities and productivity of the region by surplus supply of freshwater for livelihood, agriculture and hydropower generation.

- Necessary to understand the availability of these resources which will depleted with reduction of glaciers in long run.

- Need systematic ground-based monitoring to better understand

- Need to raise awareness and sharing information to local community

- Transboundary collaboration is very much important – single person/country can’t solve the entire issue of the landscape