Snow/Ice melt and Glacial Lake Outburst Flood in Himalayan region

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Himalayan Water Resources

- About 35% of the geographical area of India is covered by mountains and 58% of this is accounted for by the mighty Himalayas in which more than 5000 glaciers covering about 38000 km² area.

- There are 22 major river systems with about 1 million km² catchment area lying in the Himalayas, with snow and glacier melt runoff of more than 50%.

- The seasonal snow and glacier melt coming from the Himalayan Rivers is a dependable source of water for irrigation, hydroelectric power and drinking water supply.

- The hydropower generation contributes about 26% of total installed capacity in India in which Himalayan river systems contribute 78% of the total Indian hydropower potential.

- Snow melt modelling is a crucial element to predict runoff from snow-covered or glacierised areas, as well as for snow/ice melt flooding.

- The flood due to glacial lake outburst is one of the major issue because of climate change.
The Himalayan System

Western Disturbances
Nov. – March/April

Siwalik
900-1500m

Terai
<300m

SW Monsoon
June – Sep

Greater Himalaya
> 4600m

Lesser Himalaya
3600-4600m

Outer Himalaya
1500- 3500m

Tibetan Plateau
4000m

Glaciers – 10%
Winter snow cover 35-50 %
Maximum monsoon precipitation at 1500 – 3000 m asl
It is known that the effect of global climate change on hydrologic systems, especially on mountain snow and glacier melt, can modify the timing and amount of runoff in mountainous watersheds.

Streamflow simulation and forecast is of great importance to water resources management and planning, and can provide a firm basis for forecasts of water resources availability while minimizing the risk and loss from floods caused by rapid snow and glacier melt.

When the ground is frozen, the water produced by the melting snow is unable to penetrate and runs off over the ground surface into streams and lakes.

The situation can become of even greater concern if the rising snowmelt runoff is compounded by runoff from heavy rainfall.
Glacial Lake And Glacial Lake Outburst Flood (GLOF)

Glacial dammed lakes are formed by accumulation of water from the melting of Snow and Ice cover and by blockage of end moraines.

A glacial lake outburst flood (GLOF) can occur when a lake contained by a glacier or a terminal moraine dam fails.

The bursting of moraine-dammed lakes is often due to the breaching of the dam by the erosion of the dam material as a result of overtopping by surging water or piping of dam material.

GLOF STUDIES HAVE BEEN CARRIED OUT FOR LAKES IN THE BASINS OF GHARWAL HIMALAYA, EASTERN HIMALAYA AND BHUTAN HIMALAYS
SNOW AND GLACIER MELT
Location of the study area and meteorological stations in the Satluj basin

Jan 11, 2004

Feb 02, 2004

Mar 26, 2004

May 02, 2004

Jul 08, 2004

Aug 03, 2004

Sep 19, 2004

Oct 16, 2004

Nov 01, 2004

Satluj Basin

Channel-2

Channel-1

Channel-1
Snow Cover Depletion Curve

Weekly maximum % SCA

Time (in weeks)

01 Jan 03  14 Mar 03  17 May 03  20 Jul 03  22 Sep 03  25 Nov 03  18 Feb 04  30 Apr 04  25 Jun 04  28 Aug 04  31 Oct 04  02 Dec 04

Satluj  Chenab  Ravi  Beas
Lapse Rate estimation from MODIS LST maps

\[
\begin{align*}
(A) & \quad 02 \text{ Feb 2004} \\
\text{Land Surface Temperature (°C)} & \quad \text{Elevation (m)} \\
y &= -0.0072x + 23.714 \\
R^2 &= 0.9467
\end{align*}
\]

\[
\begin{align*}
(B) & \quad 01 \text{ Mar 2004} \\
\text{Land Surface Temperature (°C)} & \quad \text{Elevation (m)} \\
y &= -0.0074x + 32.452 \\
R^2 &= 0.9383
\end{align*}
\]

\[
\begin{align*}
(C) & \quad 26 \text{ Mar 2004} \\
\text{Land Surface Temperature (°C)} & \quad \text{Elevation (m)} \\
y &= -0.0063x + 33.628 \\
R^2 &= 0.7877
\end{align*}
\]

\[
\begin{align*}
(D) & \quad 16 \text{ Oct 2004} \\
\text{Land Surface Temperature (°C)} & \quad \text{Elevation (m)} \\
y &= -0.0062x + 28.797 \\
R^2 &= 0.9369
\end{align*}
\]

\[
\begin{align*}
(E) & \quad 01 \text{ Nov 2004} \\
\text{Land Surface Temperature (°C)} & \quad \text{Elevation (m)} \\
y &= -0.0059x + 27.512 \\
R^2 &= 0.9097
\end{align*}
\]

\[
\begin{align*}
(F) & \quad 20 \text{ Nov 2004} \\
\text{Land Surface Temperature (°C)} & \quad \text{Elevation (m)} \\
y &= -0.0068x + 26.763 \\
R^2 &= 0.8446
\end{align*}
\]
METHODOLOGY

TEMPERATURE
- SEASONAL LAPSE RATE
  - DISTRIBUTION OF TEMPERATURE

SNOW COVER AREA
- SNOWMELT CONTRIBUTING AREA
  - DISTRIBUTION OF SNOW
    - SNOW

PRECIPITATION
- FORM OF PRECIPITATION
  - RAIN
    - DISTRIBUTION OF RAIN
      - RAIN OVER SNOW AND GLACIER FREE AREA

SNOWMELT + RAIN + RAINMELT
- RAIN + RAIN MELT
  - DISTRIBUTION OF RAIN

DIRECT SURFACE RUNOFF FROM SNOW COVERED AREA
- ACCOUNTING OF LOSSES
  - INFILTRATION
    - BASEFLOW
      - ROUTING

ACCOUNTING OF LOSSES
- INFILTRATION
  - DIRECT SURFACE RUNOFF FROM SNOW GLACIER FREE AREA

TOTAL STREAM FLOW AT BASIN OUTLET
Main steps in modelling are as follows:

- Division of Basin Into Elevation Bands
- Processing of Meteorological Data
  - Temperature Distribution
  - Precipitation Distribution
- Variability of Snow Covered Area
- Form of Precipitation
- Melt due to rain
- Degree Day Factor for Snow and Ice
- Routing of Surface and Sub Surface Flow
Simulation of Runoff (2000-2001)

Fixed TLR (0.65 °C/100 m)

2000-2001
$R^2=0.92$

Seasonally varying TLR

2000-2001
$R^2=0.93$
Simulation of Runoff (2001-2002)

Fixed TLR (0.65 °C/100 m)

2001-2002

$R^2=0.78$

Seasonally varying TLR

2001-2002

$R^2=0.83$
ASSESSMENT AND SIMULATION OF GLACIER LAKE OUTBURST FLOODS IN HIMALAYAN REGION

To estimate the flood due to GLOF

Valley planning and flood management

To formulate emergency procedures such as warning system, evacuation plan etc.

To identify and solve unexpected flood problems due to accidents

To remove fear in public and make the public aware of the risk

To analyze past accidents for advancement of the state of art
For estimating the Glacial Lake Outburst flood, the following approach and methodology has been adopted:

Inventory of glacier and glacial lakes

Finding out the potentially dangerous glacial lakes

Estimation of Glacial lake volume and finalisation of Glacial lakes for GLOF simulation

Estimation of breach parameter for GLOF/dam breach simulation and the consequent dam breach flood using MIKE11 model

Channel routing of dam breach flood through the entire reach of river from the GLOF site to the site to get the magnitude of flood peak at site.
IDENTIFICATION OF GLACIAL LAKES

Normalized Difference Water Index

\[ \text{NDWI} = \frac{(\text{GREEN} - \text{NIR})}{(\text{GREEN} + \text{NIR})} \]

GREEN is a band that encompasses reflected green light and NIR represents reflected near-infrared radiation.

The selection of these wavelengths was done to:
1. Maximize the typical reflectance of water features by using green light wavelengths
2. Minimize the low reflectance of NIR by water features; and
3. Take advantage of the high reflectance of NIR by terrestrial vegetation and soil features.
Algorithm to automatically classify glacial lakes on IRS Images, using a decision tree. $T_i$ represents a threshold, whose value is determined empirically on each scene by visual inspection.
CRITERIA FOR IDENTIFICATION OF DANGEROUS LAKE

Rise in lake water level

In general the lakes which have a volume of more than 0.01 km³ are found to have past events. A lake which has a larger volume than this is deeper, with a deeper part near the dam (lower part of lake) rather than near the glacier tongue, and has rapid increase in lake water volume is an indication that a lake is potentially dangerous.

Activity of supraglacial lakes

Groups of closely spaced supraglacial lakes of smaller size at glacier tongues merge as time passes and form bigger lakes. These activities of supraglacial lakes are indications that the lakes are becoming potentially dangerous.
POSITION OF LAKES

The potentially dangerous lakes are generally at the lower part of the ablation area of the glacier near to the end moraine, and the mother glacier should be sufficiently large to create a potentially dangerous lake environment.

The valley lakes with an area bigger than 0.1 km² and a distance less than 0.5 km from the mother glacier of considerable size are considered to be potentially dangerous.

DAM CONDITIONS

The natural conditions of the moraine damming the lake determine the lake stability. Lake stability will be less if the moraine dam has a combination of the following characteristics:

• narrower in the crest area
• no drainage outflow or outlet not well defined
• steeper slope of the moraine walls
• ice cored
• breached and closed in the past and refilled again with water seepage flow at moraine walls
CONDITION OF ASSOCIATED MOTHER GLACIER

The following general characteristics of associated mother glaciers can create danger to moraine-dammed lakes:

- hanging glacier in contact with the lake,
- bigger glacier area,
- fast retreating,
- debris cover at glacier tongue area,
- steep gradient at glacier tongue area,

PHYSICAL CONDITIONS OF SURROUNDINGS

- potential rockfall/slide (mass movements) site around the lake which can fall into the lake suddenly
- snow avalanches of large size around the lake which can fall into the lake suddenly
- neo-tectonic and earthquake activities around or near the lake area
- climatic conditions of successive years being a relatively wet and cold year followed by a hot and wet or hot and arid year
Glacier and Glacier lake mapping

Drainage network and Length of stream d/s lake

DEM of the basin

Cross Section at regular interval downstream of lake

Area and Volume of the lake

Breach width and Depth

100 year return flood if available

GLOF SIMULATION: INPUT REQUIRED
MIKE11 DAM BREAK MODELLING

- Hydrodynamic modeling
  - Estuaries
  - Rivers
  - Irrigation systems
  - Dambreak
  - Controllable Weirs
  - Flood Control
  - Flood Forecasting

- Water Quality modeling
  - Balance of Dissolved Oxygen, Ammonia, Nitrate etc.
  - Eutrophication
  - Heavy Metals
  - Wetlands

- Advection Dispersion modeling
  - Salinity Intrusion
  - Temperature
  - Pollutant Transport

- Sediment Transport modeling
  - Cohesive Sediment
  - Non-cohesive Sediment
  - Potential Transport
  - Morphological modelling
LAKE DEPTH

The empirical relations as available by Huggel et al. (2002) is:

The lake volume \( D = 0.104 \, A^{0.42} \)

where \( D \) is the depth of lake in m and \( A \) is the lake area in m\(^2\).

LAKE VOLUME

The empirical relations as available by Huggel et al. (2002) is:

The lake volume \( V = 0.104 \, A^{1.42} \)

where \( V \) is the lake volume in m\(^3\) and \( A \) is the lake area in m\(^2\).
Chorabari Lake outburst - (June 17, 2013)
Satellite pictures show that the glacial regions above Kedarnath had received fresh and excess snowfall when heavy rainfall hit the region. (Source NRSC, 2013)
GLOF HYDROGRAPH AT CHAMKHARCHU H.E. PROJECT BHUTAN

V = 54.18 Mm³

Chubda Lake

D = 40 m

4920 m

118.84 km

900 m

Project Site (chamkhar)

10251.71 cumec

5068.59 cumec

2 hour 10 minutes

Time Series Discharge
KURI-GONGRI HE PROJECTS, BHUTAN

V = 11.62 Mcum
D = 40 m

Kuri basin

4690 m

194 km

Cross-section of Kuri Basin

8478.9 cumec
6821.0 cumec

1 hour 50 minutes
Gongri basin

45.56 Mm³
D=25 m

4564 m
114.3 km

Cross section Of Gongri Basin

GLOF
GONGRI

4685.3 cumec
1 hour 20 minutes

3850.5 cuemc
LACHUNG HE PROJECT, SIKKIM, INDIA

V = 54.18 Mcum
D = 16 m

919.04 cumec
751.10 cumec
50 minutes
Site-I

919.04 cumec
749.29 cumec
Site-II

4812 m
Site-I 32 km
Site-II 36 km
Site-III 38 km

Potential Flood Hazard Map

Site-I

Site-II

Site-III
Cross-section of Twang Basin

V = 11.62 Mcum
V = 10.85 Mcum
D - 25 m

4564 m
36 km
1525 m

4348 m
40 km

2959.00 cumec
2791.56 cumec

12 minutes

3120.00 cumec
2792.05 cumec

12 minutes
In 2004, the size of the glacier lake was 0.19 sq km and in 2008, it increased up to 0.203 sq km.
## RECENT GLOF EVENTS - BHUTAN

<table>
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<th>S.No</th>
<th>DATE</th>
<th>RIVER BASIN</th>
<th>LAKE</th>
<th>CAUSE OF GLOF</th>
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<td>1</td>
<td>1957</td>
<td>Pho Chu</td>
<td>Tarina Tso</td>
<td>Not known</td>
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<td>Pho Chu</td>
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<td>4</td>
<td>7 Oct 94</td>
<td>Pho Chu</td>
<td>Luggye Tso</td>
<td>Moraine collapse</td>
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<tr>
<td>S.No.</td>
<td>DATE</td>
<td>RIVER BASIN</td>
<td>LAKE</td>
<td>CAUSE OF GLOF</td>
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<td>Tamakoshi</td>
<td>Chubung</td>
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<td>2</td>
<td>3 Sep 98</td>
<td>Dudh Koshi</td>
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<td>Madi River</td>
<td>Kabache Lake</td>
<td>Moraine collapse</td>
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<td>4</td>
<td>8 Aug 04</td>
<td>Madi River</td>
<td>Kabache Lake</td>
<td>Moraine collapse</td>
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METHODS FOR MITIGATING THE IMPACT OF GLOF

REDUCING THE VOLUME OF LAKE WATER
Possible peak surge discharge from a GLOF could be reduced by reducing the volume of water in the lake. In general, any one or combination of the following methods may be applied for reducing the volume of water in the lake:

Controlled breaching
Controlled breaching can be carried out by blasting, excavation, or even by dropping bombs from an aircraft.

Construction of an outlet control structure
For more permanent and precise control of lake outflows, rigid structures made out of stone, concrete, or steel can be used.

Pumping or siphoning out the water from the lake, and

Making a tunnel through the moraine dam
Tunneling through moraines or debris barriers, although risky and difficult because of the type of material blocking the lake, has been carried out in several countries.
PREVENTATIVE MEASURES AROUND THE LAKE AREA

Any existing and potential source of a larger snow and ice avalanche, slide, or rock fall around the lake area, which has a direct impact on the lake and dam has to be studied in detail. Preventative measures have to be taken such as removing masses of loose rocks to ensure there will be no avalanches into the lake.

Real-time monitoring, early warning systems and preparedness education are the most beneficial ways to minimize risk.

Preparedness – hazard mapping, improving communication, education to create awareness
Glacier and snow-melt have major contribution to the river flows in the region. It is necessary to characterize the glaciers in different climatological regions of the basin.

The rate, volume and timing of snow melt are likely to change, therefore, impact of climate change on the snowmelt runoff and total streamflow of the large Himalayan rivers should be investigated using GCMs output as input to the calibrated hydrological models.

Studies on the trend of changes in snow cover over the Himalayas/basins along with retreat of glaciers need immediate emphasis.

Concluding Remarks
Concluding Remarks

- Climate warming will increase the frequency and risk of GLOFs
- Regular mapping and monitoring of lakes are needed
- Potentially dangerous glacial lakes must be provisionally identified and prioritized for further investigation
- Potentially dangerous lakes must be monitored on a continuous basis
- High resolution time series satellite image are useful for this purpose
- Appropriate measures to reduce the potential risks from these lakes
THANKS