INTEGRATED GLACIAL LAKE OUTBURST FLOOD (GLOF) STUDY FOR LOHIT BASIN, ARUNACHAL PRADESH

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ABSTRACT

A large number of hydro electric projects are coming up in the Himalayas in India and Bhutan. The snowfed catchment area of these and/or retreating processes of a glacier. The lakes located at the snout of the glacier are mainly dammed by the lateral or end moraine, where there is high tendency of breaching. Such lakes could be dangerous as they may release a large quantity of water in the event of their breaching. Breaching and the instantaneous discharge of water from of such lakes can cause flash floods enough to create enormous damage in the downstream areas where such projects are located. 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.Since these moraine dams are naturally formed with highly porous soil material inside the dam body, there is a strong possibility of breaching of these moraine dams either due to piping or due to overtopping therefore releasing a sudden discharge of significant magnitude, endangering the safety of the HE hydroelectricproject being planneddownstream. Hence it has become necessary for the project planners and designers to account for the glacial lake outburst flood (GLOF) also along with the design flood for deciding the spillway capacity of projects located in similar hydro-meteorological regions. Though the glacial lake outburst flood peak may be of very high magnitude just downstream of the lake, its attenuation will be quite significant as the flood wave traverses through the downstream valley. The GLOF peak at any project location will depend upon the attenuation pattern of the GLOF hydrograph, which can only be obtained by a dam break simulation coupled with the hydrodynamic routing. In the present paper the methodology adopted for integrated glacial lake outburst flood estimation at three project sites in the Lohit basin namely Kalai-I, Kalai-II and Hutong-II HE Projects has been discussed.

1.0 INTRODUCTION

In the Himalayan region, major rivers are originating from glaciers and larger portion of the freshwater resources are locked up in ice and snow. During the last few decades there has been a rapid retreat of glaciers which has created many precarious glacial lakes in the Himalayan region. A glacial lake is defined as water mass existing in a sufficient amount and extending with a free surface in, under, beside, and/or in front of a glacier and originating from glacier activities and/or retreating processes of a glacier. The isolated lakes found in the mountains and valleys far from the glaciers may not have a glacial origin. Due to the rapid rate of ice and snow melt, possibly caused by global warming, accumulation of water in these lakes has been increasing rapidly in Himalayas. The isolated lakes above 3,500 masl are considered to be the remnants of the glacial lakes left due to the retreat of the glaciers. The lakes located at the snout of the glacier are mainly dammed by the lateral or end moraine, where there is high tendency of breaching. Such lakes could be dangerous as they may hold a large quantity of water. Breaching and the instantaneous discharge of water from such lakes can cause flash floods enough to create enormous damage in the downstream areas.

A Moraine Dammed lake formed in the retreating process of glacier is filled with melt water and rainwater from the drainage area behind the lake and starts flowing from the outlet of the lake even in the winter season when there is minimum flow. Moraine Dammed glacial lakes, which are still in contact or very near to the glaciers, are usually dangerous. 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. In general, the potentially dangerous status of Moraine Dammed lakes can be defined by the conditions of the damming material and the nature of the mother glacier. The valley lakes with an area bigger than 0.1 km^2 and a distance less than 0.5 km from the mother glacier of considerable size are considered to be potentially dangerous. Generally, the bigger Valley glaciers with tongues reaching an elevation of below 5,000 masl have well-developed glacial lakes. Even the actively retreating and steep hanging glaciers on the banks of lakes may be a potential cause of danger.

2.0 CLASSIFICATION OF GLACIAL LAKES

The glacial lakes are classified into Erosion, Valley trough, Cirque, Blocked, Moraine Dammed (Lateral Moraine and End Moraine Dammed lakes) and Supraglacial lakes.

Erosion lakes

Glacial Erosion lakes are the water bodies formed in a depression after the glacier has retreated. They may be Cirque type (Fig-1) and trough Valley type lakes and are stable lakes. These Erosion lakes might be isolated and far away from the present glaciated area. These glacial lakes occupy the lowlands or emptying cirques eroded by ancient glaciers. These lakes could be dangerous if potential snow avalanche exists.

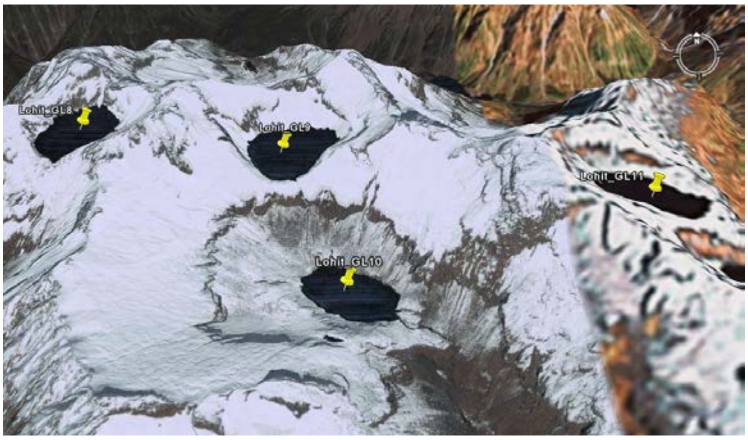

Fig-1: Cirque lakes formed in the Lohit basin

Supraglacial lakes

The Supraglacial lakes develop within the ice mass away from the moraine with dimensions of 50 to 100 meters (Fig-2). These lakes may develop in any position of the glacier but the extension of the lake is less than half the diameter of the Valley glacier. Shifting, merging, and draining of the lakes are the characteristics of the Supraglacial lakes. The merging of lakes results in expansion of the lake area and storage of a huge volume of water with a high level of potential energy. The tendency of a glacial lake towards merging and expanding indicates the danger level of the GLOF.

Fig-2: Supraglacial lakes formed in the Thorthormi glacier, Bhutan

Moraine Dammed lakes

In the retreating process of a glacier, glacier ice tends to melt in the lowest part of the glacier surrounded by Lateral Moraine and End Moraines. As a result, many supraglacial ponds are formed on the glacier tongue. These ponds sometimes enlarge to become a large lake by interconnecting with each other and have a tendency to deepen further. A Moraine Dammed lake is thus born. The lake is filled with melt water and rainwater from the drainage area behind the lake and starts flowing from the outlet of the lake even in the winter season when there is minimum flow (Fig-3).

There are two kinds of moraine: ***an ice-cored moraine and an ice-free moraine***. Before the ice body of the glacier completely melts away, glacier ice exists in the moraine and beneath the lake bottom. The ice bodies cored in the moraine and beneath the lake are sometimes called dead ice or fossil ice. As glacier ice continues to melt, the lake becomes deeper and wider. Finally, when ice contained in the moraines and beneath the lake completely melts away, the container of lake water consists of only the bedrock and the moraines.

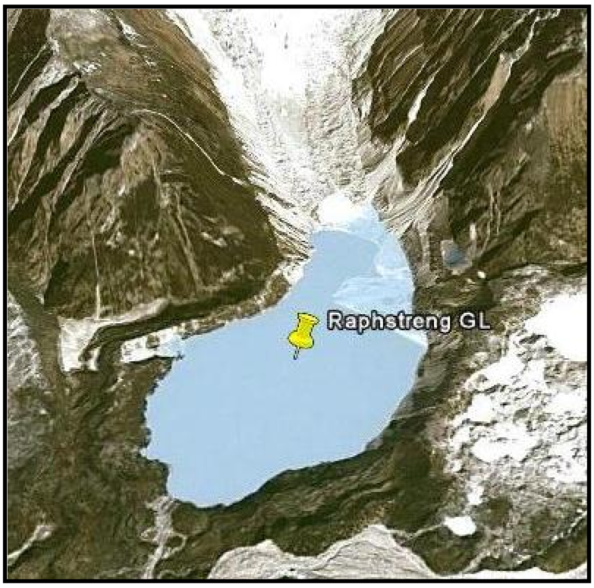

Fig-3: Moraine dammed Lake RaphstrengTso, Bhutan in contact with the glacier snout

If one follows the life span of an individual glacier, it is found that the Moraine Dammed glacial lakes build up and disappear with a lapse of time. The moraine dammed lakes disappear once they are fully destroyed or when debris fills the lakes completely or the mother glacier advances again to lower altitudes beyond the moraine-dam position. Such glacial lakes are essentially ephemeral and are not stable from the point of view of the life of glaciers. Generally, moraine dammed lakes pose a threat in the basin.

Blocking lakes

Blocking lakes are formed through glacier and other factors, including the main glacier blocking the branch valley, the glacier branch blocking the main valley, and the lakes through snow avalanche, collapse and debris flow blockade.

Ice-dammed lakes

An Ice-dammed lake is produced on the side(s) of a glacier, when an advancing glacier happens to intercept a tributary/tributaries pouring into a main glacier valley. As such, an Ice core-dammed lake is usually small in size and does not come into contact with glacier ice. This type of lake is less susceptible to GLOF than a moraine dammed lake. A glacial lake is formed and maintained only up to a certain stage of glacier fluctuation.

3.0 MECHANISM OF MORAINE-DAMMED LAKE FAILURE

Moraine dam failure and Glacial Lake Outburst Floods present one of the greatest threats in mountainous regions. In the last several centuries, many of the present moraine-dammed lakes were created by advances and retreats of valley glaciers. Moraine dams pose hazards because of their composition and location. Moraine dams are usually located downslope from steep crevassed glaciers and vertical rock slopes, and located upslope from steep canyons with easily erodible materials. Overtopping and breaching of the dam by waves generated by avalanches or glacier calving is the most common failure mechanism. The result of the dam failure is catastrophic downstream flooding. Some of the largest downstream flood peaks are produced from moraine-dam failures. Dam characteristics and failure mechanisms affect the flood peak.

End and lateral moraines are created from material pushed and piled from glacier movement along with till released when a glacier melts and recedes. End and lateral moraines form at the glacier margin (Fig-4). Till is a heterogeneous accumulation of unsorted soil, rock, and other material released from the glacier ice. End moraines are formed at the farthest limit reached by a glacier. Lateral moraines are formed along the sides of a glacier. Both terminal and lateral moraines may act as dams. A moraine-dammed glacial lake is formed as the glacier recedes from the end moraine in a mountain valley. The moraine acts as an unstable dam to water melting from the glacier.

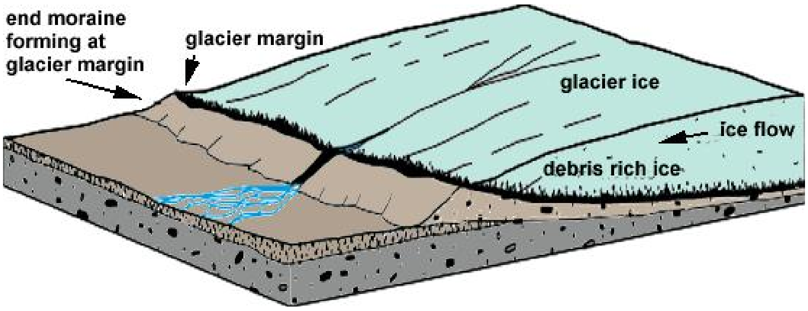

Fig-4: End moraine formation. Source: Hansel (2003)

Most moraine dams and moraine-dammed glacial lakes have a history of cyclic outburst activity. The cyclic outburst activity ends when the moraine dam is damaged by the outburst floods to the point that it can no longer hold water. As glaciers retreat, the cyclic outburst activity may travel up glacier to newly formed moraine dams and moraine-dammed lakes.

The unstable nature of moraine dams greatly increases the chances of dam failure. Many factors contribute to the unstable nature of the moraine dam. The moraine dam may contain stagnant glacier ice. Moraine dams are typically narrow and high reducing structural strength. Large lake volume above the moraine dam increases pressure against the dam. Limited freeboard between the crest of the moraine dam and the lake level reduces the height of waves needed to overtop the moraine dam. Since moraine dams have steep slopes and contain loose, poorly sorted sediment, moraine dams are highly susceptible to failure.

Moraine dam failure may be caused from one of several triggers. Large waves caused from calving glaciers or ice or rock avalanches into the lake may overtop the moraine dam as shown in Fig-5. Settlement within the dam due to voids left during deposit may reduce the freeboard or create passageways for piping to occur. Melting of stagnant glacier ice in the moraine dam may also reduce the freeboard or create passageways for piping to occur. Catastrophic glacial drainage may raise the lake level quickly and overtop the dam. Earthquakes may also cause moraine dam failure.

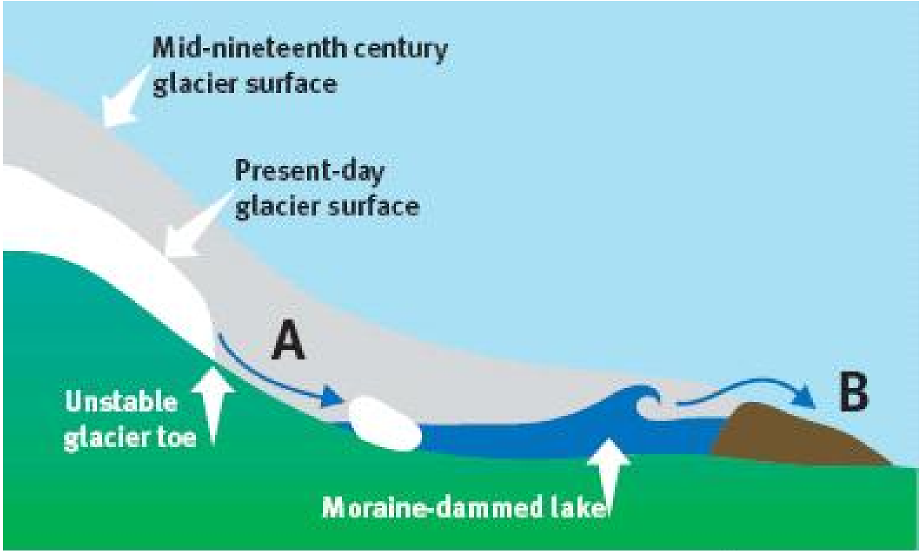

Fig-5: Moraine-dammed lake creation from glacier retreat and failure mechanism (A) Ice avalanche from glaciercausing wave. (B) Wave overtopping moraine dam. Source: Clague (2003).

4.0 GLACIAL LAKE OUTBURST FLOOD (GLOF)

The sudden failure of a moraine dam on a glacial lake can release a very large amount of water called a Glacial Lake Outburst Flood. The released water may destroy property hundreds of kilometers from the source. Although Glacial Lake Outburst Floods have occurred around the world, outburst floods in the Andes, European Alps, and Himalayas have a history of property destruction and loss of human life due to settlement. As remote mountain valleys become settled, more people and property are put in danger. Glacial Lake Outburst Floods increase to peak flow then gradually or abruptly decrease to normal levels once the water source is exhausted. Outburst flood peak flow is directly related to lake volume, dam height and width, dam material composition, failure mechanism, downstream topography, and sediment availability.

When abundant sediment is available below the dam, outburst floods may transform into debris flows. Slopes greater then 10 to 15 degrees are required for debris flows to form and be sustained. Glacial Lake Outburst Floods alter the river floodplain by eroding, transporting, and depositing large amounts of sediment. The alteration of the river floodplain may occur tens of kilometers away from the water source.

Further, moraine-dammed lakes are generally drained by rapid incision of the sediment barrier by outpouring waters. Once incision begins, the hustling water flowing through the outlet can accelerate erosion and enlargement of the outlet, setting off a catastrophic positive feedback process resulting in the rapid release of huge amounts of sediment-laden water. The onset of rapid incision of the barrier can be triggered by waves generated by glacier calving or ice avalanching, or by an increase in water level associated with glacial advance.

Factors contributing to the hazard risk of moraine-dammed glacial lake include (a) large lake volume, (b) narrow and high moraine dam, (c) stagnant glacier ice within the dam, and (d) limited freeboard between the lake level and the crest of the moraine ridge. Potential outburst flood triggers include avalanche displacement waves from (A) calving glaciers, (B) hanging glaciers, and (C) rock falls; (D) settlement and/or piping within the dam (due to progressive seepage or seismic activity); (E) melting ice-core; and (F) catastrophic glacial drainage into the lake from subglacial or englacial channels or supraglacial lakes. A schematic diagram of a hazardous moraine-dammed glacial lake is shown in Fig-6.

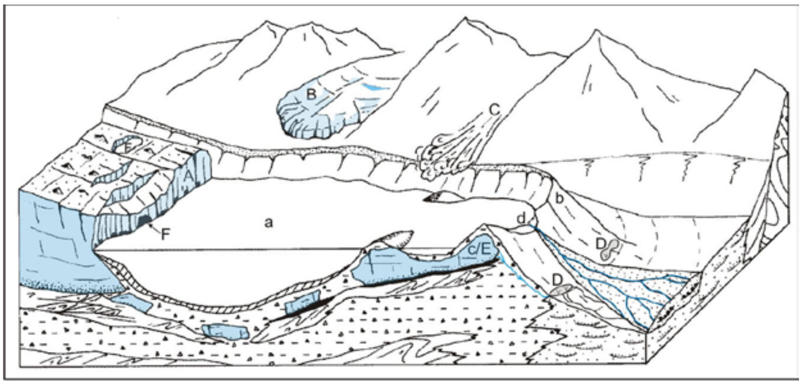

Fig-6: Schematic diagram of a hazardous moraine-dammed glacial lake

Due to extreme hazard potential of GLOF events, it is necessary to take into account the GLOF, while planning, designing and constructing any infrastructure, especially water resources projects, since these are right in the river channel and would be first victim in case of GLOF.

5.0 METHODOLOGY FOR GLOFESTIMATION

For estimating the Glacial Lake Outburst flood for any hydroelectric project the following methodology can beadopted:

- Prepare the inventory of glacial lakes for the catchment area of the projectand identifyamongst themthe potentially dangerous glacial lakesbased on the condition of lakes, dams, associated mother glaciers, and topographic features around the lakes and glaciers.

- Estimate the water spread area and the volume of lakes. Based upon detailed criticality analysis considering various factors viz volume of water stored in the lake, distance of the lake from the project site and average slope of the river from the lake upto the project site, identify the lake or possible combination of lakes to be considered for GLOF estimation.

- Estimatethe breach parameters for GLOF/dam break simulation.Run the dam break simulation using any hydrodynamic mathematical model like MIKE11/HEC-RAS and Channel route the lake outburst flood through the entire reach of river from the lake to project site to get the magnitude of flood peak at project site.

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6.0 INTEGRATED GLOFSIMULATION FOR KALAI-I, KALAI-II AND HUTONG-II HE PROJECTSIN LOHIT BASIN (ARUNACHAL PRADESH)

The Lohit basin lies between Latitude 27°34’ N and 29°36’ N and Longitude 95°38’ E and 97° 44’ E. The snowy mountains in the upper catchment, dense evergreen forests in the lower hills, innumerable rivers and rivulets are major topographical characteristics of the Lohit basin. Kalai-I, Kalai-II and Hutong-II HE projects are the part of the cascade development of Lohitriver. The catchment area of Lohitriver at Hutong-II, Kalai-II and Kalai-I HE projects is 16272 sq.km, 15654 sq.km and 14168 sq.km respectively. The proposed dam for Kalai-I HEP is located at latitude $27^{0}55^{'}08^{''}$N and longitude $96^{0}57^{'}14^{''}$E. The proposed dam for Kalai-II HEP is located at latitude $27^{0}54^{'}20^{''}$N and longitude $96^{0}47^{'}57^{''}$E. Out of these three projects, Kalai-II and Kalai-I HEP are proposed about 20 km upstream and 39 km upstream of Hutong-II HEP. The proposed dam for Hutong-II HEP is located at latitude $28^{0}00^{'}14^{''}$N and longitude $96^{0}42^{'}07^{''}$E. The appreciable area of Lohit River lies in the Chinese territory. About 27% of the river catchment up to Hutong-II project site is covered with permanent snow, 46% is rain fed and the remaining 26 % has seasonal snow, but is rainfed in late monsoon.

There are more than two hundred glacial lakes in the catchment area of the projects. Based on the possible combination of adjacent glacial lakes in future by making the 3D models, lake surface area and their distance from the project site, the criticality analysis has been carried out to find out the most critical glacial lakes, which can be considered for integrated GLOF simulation of the Kalai-I, Kalai-II and Hutong-II HE projects. After the criticality analysis,lakeLohit-GL4 (Fig-7) with water spread area of about 100.93 hectare and 179 km distance from the Hutong-II, 159 km from Kalai-II and 140 km from Kalai-I dam siteshas been finalized for the GLOF simulation. In the absence of any hydrographic survey data it is not possible to get the exact volume of glacial lakes. Moreover the hydrographic survey at the locations of glacial lakes is also not possible due to very dangerous terrain. However to get a practical estimate of the lake volume some methodologies have been suggested by International Centre for Integrated Mountain Development (ICIMOD) and Christian Huggel. As per ICIMOD the average depth for moraine lakes can be adopted as 30 m. The water reserves of different types of glacial lakes can be obtained by multiplying their average depth by their area. As per Huggel's empirical equation the depth and volume of glacial lake can be estimated as follows:

$D = 0.104A^{0.42}$
$V = 0.104A^{1.42}$
A = Surface/Water spread area of glacial lake (m^2)
D = Depth of glacial lake (m).
V = Volume of glacial lake (m^3)

The volume of glacial lake Lohit-GL4 calculated using the above two methods gave almost thesame estimate. Hence for the purpose of GLOF simulation average depth of the lake has been adoptedas 32 m. The average volume of the lake based on the above two different approacheshas been adopted as 32 MCM. Further considering the location of the lake and its size, it has been assumed that a volume of about 26 MCM (80% of 32 MCM) will be released. The corresponding depth of breaching section has been adopted as 26 m.

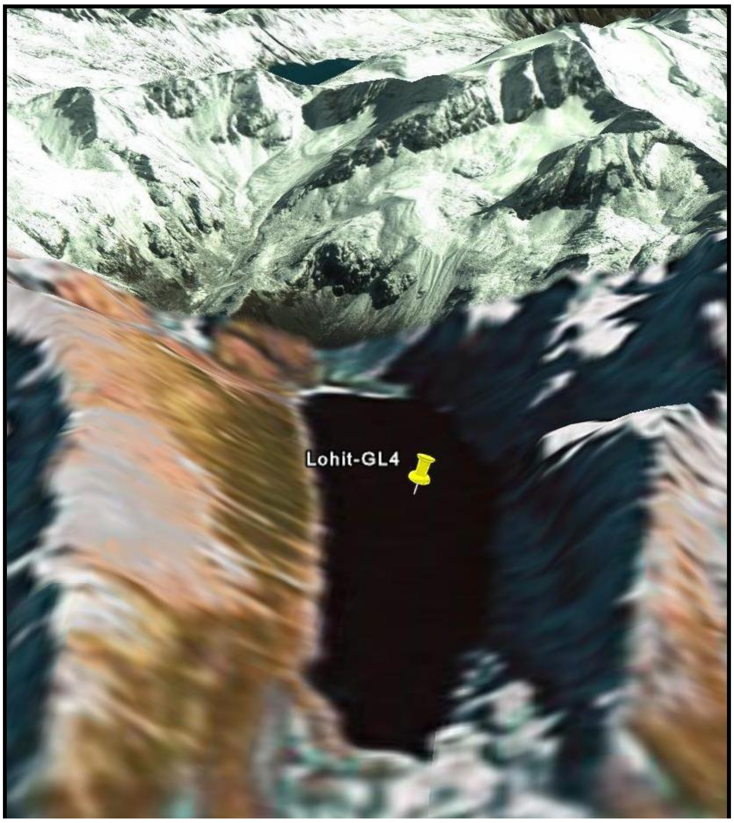

Fig-7: Glacial lake Lohit-GL4

The Kalai-I, Kalai-II and Hutong-II projects are located at 140 km, 159 km and 179 km respectively from the lakeLohit-GL4. For the purpose of integrated GLOF study, the cross sections of Lohitriver,at every 3 km(approx) interval,for its 182 km reach have been used in MIKE11 model set up. The downstream boundary of the GLOF model set up has been applied at 182 km i.e. 3 km downstream of Hutong-II HEP site. For this 182 km study reach of the river, the drop in river bed level is about 3000 m. The GLOF simulation has been carried out using one dimensional mathematical model MIKE11. The relative location of the lake Lohit-GL4 and projectsis given in Fig-8.

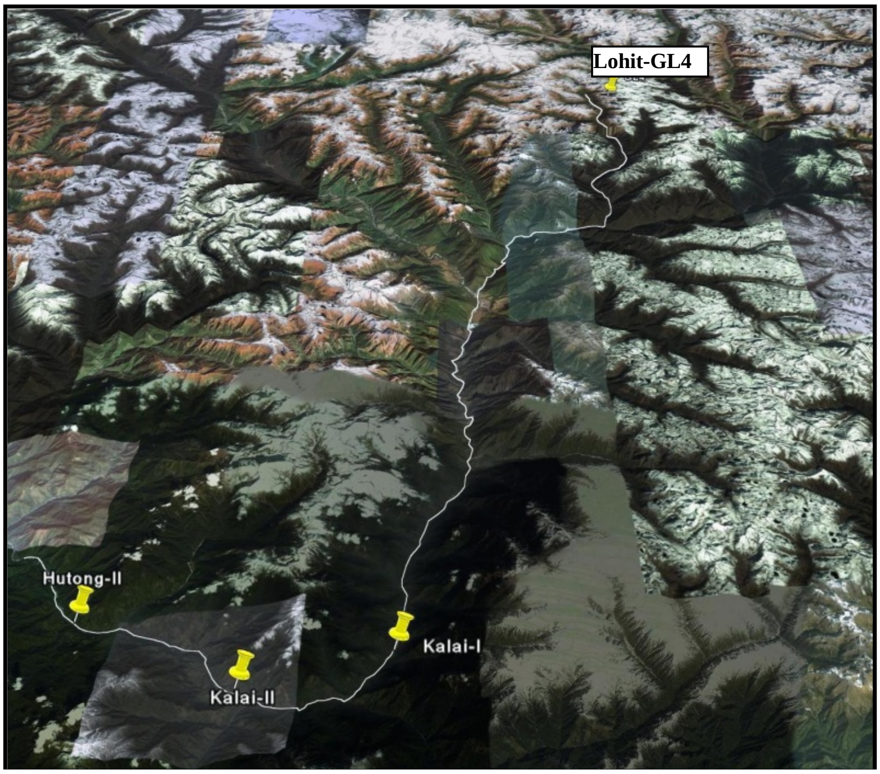

Fig-8: Schematic diagram showing Lohit-GL4, Kalai-I, Kalai-II and Hutong-II HE Projects used in MIKE11 model set up for integrated GLOF simulation

The breach parameters adopted for the GLOF simulation are:average breach width 80m, breach depth 26m and breach development time 0.5 hour.The following two initial conditions of discharge in the Lohitriver are considered for simulation:

i) Steady discharge corresponding to average annual runoff
ii) Steady discharge corresponding to 100 year return period flood

The average annual flow and 100 year flood at respective project site is given below:

Project Name	Distance from Lohit-GL4lake	Catchment area	Average annual discharge	100 yr flood
	(km)	(km^2)	(cumec)	(cumec)
Hutong-II	179	16272	949	11923
Kalai-II	159	15654	885	11582
Kalai-I	140	14168	772	10747

The average annual flood and 100 yr flood has been distributed based on the catchment area proportioning and thenimpinged as constant steady discharge at different locations alongthe river in the model set. A catchment area plan showing the location of the projects and sub catchments polygon is given in Fig-9.

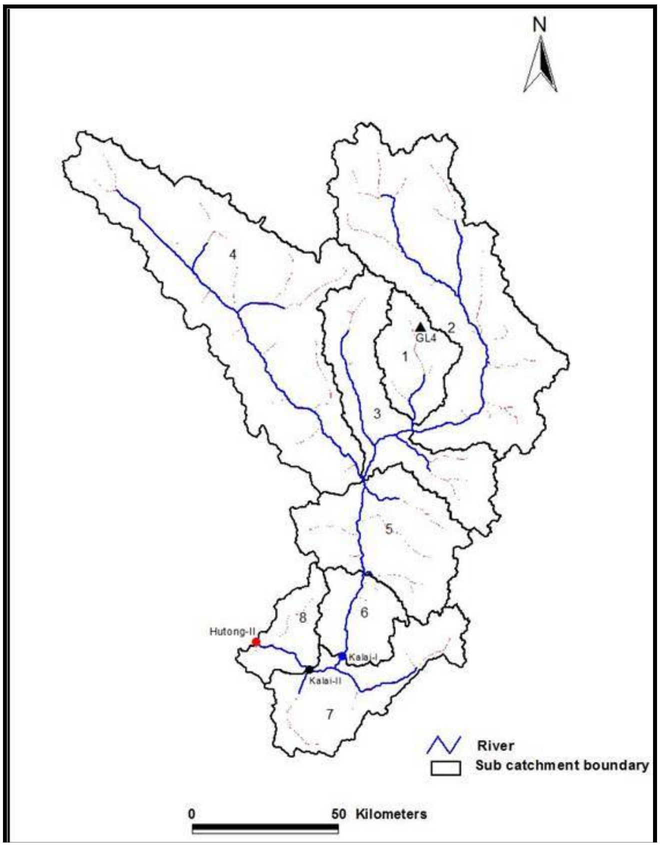

Fig-9: Catchment area plan of Lohitriver for Hutong-II, Kalai-II and Kalai-I HE Projects along with location of Lohit-GL4

The area of sub-catchments and distribution of flood is given in Table-1. For integrated GLOF study the average annual flow and 100 year flood of Kalai-I HEP has been first distributed based on the catchment area proportioning up to sub catchment up to sub catchment 6. After sub catchment 6 the difference of mean annual flow and 100 year flood of Kalai-II and Kalai-I has been added as lateral inflow for sub catchment 7. Similarly after sub catchment 7 the difference of mean annual flow and 100 year flood of Hutong-II and Kalai-II has been added as lateral inflow for sub catchment 8.

Table-1: Area of sub catchments of Lohit river as per Fig-6.3 used for annual mean flow and 100 year flood distribution

Sub catchment no.	Area (km^2)		Distribution of average annual flow	Distribution of 100 year flood	Impingement location (km) d/s of Lohit-GL4
1	797		43	605	0.0001
2	4197		229	3184	44
3	1823		99	1383	74
4	4778		260	3624	74
5	1836		101	1392	110
6	737	Total of (1 to 6) = 14618 km^2 (Catchment area of Kalai-I, located at 140 km from Lohit-GL4)	40	559	138.2
7	1486	Total of (1 to 7) = 15654 km^2 (Catchment area of Kalai-II, located at 159 km from Lohit-GL4)	(885-772) 113	(11582-10747) 835	157.2
8	618	Total of (1 to 8) = 16272 km^2 (Catchment area of Hutong-II, located at 179 km from Lohit-GL4)	(949-885) 64	(11923-11582) 341	177.2

The estimatedGLOF peak and its travel time at different project sites for two differentinitial dischargeconditionsin theriver corresponding to i) average annual runoff and ii) 100 year return period flood is given in Table-2.

Table-2:GLOF Peak and its travel time for Kalai-I, Kalai-II and Hutong-II HE Projects

Case No.	Initial condition of discharge in river for GLOF simulation	GLOF peak just d/s of lake Lohit-GL4	GLOF peak at Project site	*Travel time of GLOF wave up to project site
	(cumec)	(cumec)	(cumec)	(hour)
A)	**Kalai-I HE Project**			
i	Average annual flow	9394	1586	6.25
ii	100 yr return period flood	9394	2807	4.00
B)	**Kalai-II HE Project**			
i	average annual flow	9394	1519	7.20
ii	100 yr return period flood	9394	2690	4.60
C)	**Hutong-II HE Project**			
i	Average annual flow	9394	1447	8.20
ii	100 yr return period flood	9394	2615	5.20

From Table-2 it can be seen that for all the three project sites, the GLOF peak is more and its travel time is less, for the initial condition of river corresponding to 100 year flood.Further, considering the hydro-meteorological condition of the project sites there can be possibility of occurrence of the GLOF during the extreme flooding condition of the rivers. Hence, the Glacial Lake Outburst Flood (GLOF) for Kalai-I, Kalai-II and Hutong-II HE Project has beenadopted as 2807 cumec, 2690 cumec and 2615 cumec respectively. The plot of GLOF hydrograph at the above project sites is given in Fig-10.

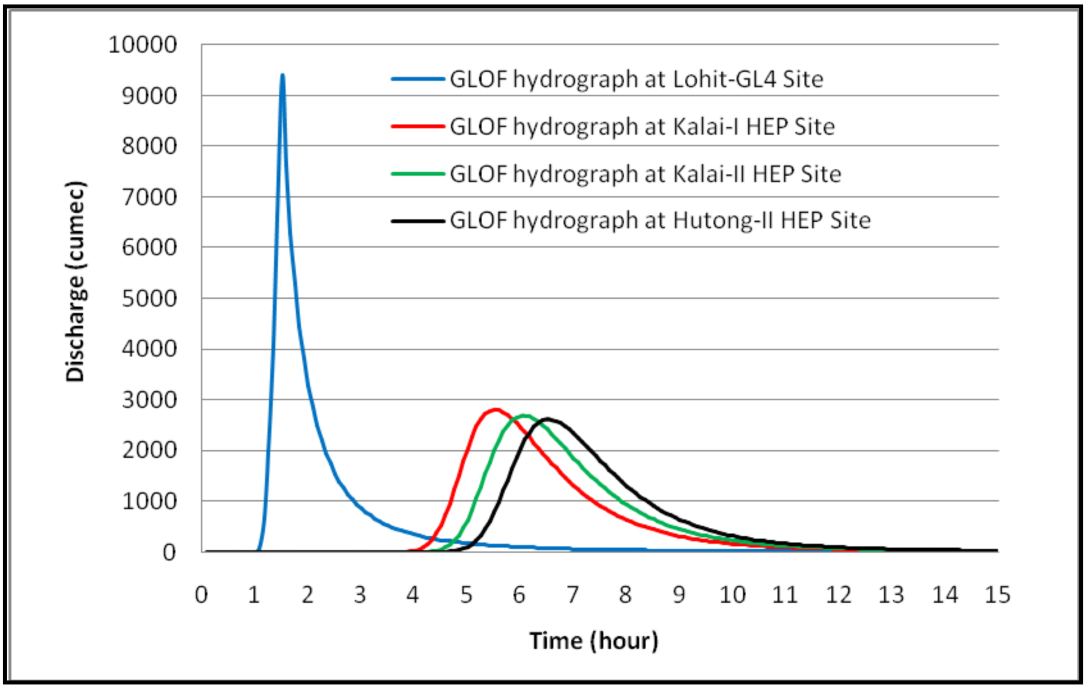

Fig-10: GLOF hydrograph at Kalai-I, Kalai-II and Hutong-II HE Project site

7.0 CONCLUSION

Though the glacial lake outburst flood peak may be of very high magnitude just downstream of the lake its attenuation will be quite significant as the flood wave traverses through the downstream valley. The attenuation pattern will depend upon the physiographic characteristics of the downstream valley and also the time base of the peak segment of the GLOF hydrograph. Normallythe time base of the peak segment of the GLOF hydrograph will be small due to relatively small storage capacity of the moraine dammed glacial lakes hence its attenuation will be significant at the flood wave passes through the downstream valley. The GLOF peak at any project location generallydepends upon its riverine distance from the source and its translation time depends upon the initial discharge condition in the river. More severe initial flood condition of the river will accelerate the translation of GLOF resulting in less warning time. Further, the very high sediment load associated with the lake outburst flood may bring the significant change in the river morphology up to few kilometers from its source and also in the reservoir bed level for run of the river schemes.

Disclaimer: The views expressed in the paper are purely personal and not necessarily the views of the organisation they belong to.

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