A COMPARATIVE MODELING STUDY OF GLACIAL LAKE AND ASSOCIATED GLACIAL LAKE OUTBURST FLOODS AT DUGAR HYDRO-ELECTRIC PROJECT IN CHENAB RIVER BASIN

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ABSTRACT

Glacial lakes are common in the upper reaches of glacierised basin such as basins in Himalayan regions. They are formed by storage of melting water from snow and glacier ice. Most of these glacial lakes are dammed by unstable lateral or end moraines. These lakes normally drain their water through seepage. But as the global warming has increased the pace of melting of snow and glaciers, some glacial lakes are getting bigger in size and accumulating more water with time. Such bigger glacial lakes holding large quantity of water, if breached, discharges huge amount of stored water instantly causing flash floods, known as Glacial Lake Outburst Floods (GLOFs). It could create havoc in downstream areas. Hence GLOF must be taken into account while planning, designing and constructing any infrastructure in downstream. Specifically, water resource projects shall be of prime concern for experts involved in water sector as they are situated on the stream path and could breach leading to further catastrophe and financial loss. In the present study, glacial lakes, that may pose a threat for under planned Dugar Hydro-Electric Project (HEP) in Chenab basin, have been identified. By criticality analysis, three glacial lakes have been selected as potentially dangerous based on their water surface extent and distance from project site. The water surface area of one glacial lake was found to be increased by 81% from 2014 to 2020 using remote sensing analysis. The increase in lake size also led to increase in GLOF by 50% at project site. The motive of this study is to assess the increase in GLOF due to increase in lake area. This study tries to impart a sense of understanding to the water resource community regarding the expansion in both glacial lakes and resulted GLOF and try to present a road map for various future researches.

***Keywords**: Glacier retreat, Glacial lake expansion, Glacial lake outburst flood (GLOF), Hydrodynamic channel routing, MIKE-11, Dam break*

1. INTRODUCTION

A number of water resource projects have been constructed in Indian River basins of Himalayan region and many are in different stages of planning and construction. The catchment of most projects in Himalayan region includes snow cover and glaciers. Due to the climate change induced global warming; the temperature in the Himalayas during the past few decades has shown constant increment resulting in recession of glaciers. (1, 2, 3, 4, 5, 6, 7) As a result of this climate change induced global warming; glacial lakes are increasing significantly both in terms of number and size. This has made them susceptible to GLOF. (8, 9, 10) The type of glacial lakes can be erosion lakes, cirque lakes, moraine dammed lakes, etc. (2, 11) However moraine dammed glacial lakes are considered as potentially dangerous lakes due to its unstable and unconsolidated nature.

The moraine dams are naturally formed dams with ice and highly porous soil material inside the dam body. Due to receding of glaciers at a rapid rate, size of glacial lakes is also increasing concomitantly. The moraines that are damming such glacial lakes may breach in future either due to overtopping or piping, releasing a sudden discharge. The sudden discharging caused due to breaching of such glacial moraine lakes releases enormous volume of water and debris in devastating manner is known as Glacial Lake Outburst Floods (GLOFs) (12). These GLOF events endanger the safety of hydroelectric projects being planned in downstream. Hence, it has become utmost important for water resources planners to account for the GLOF along with the design flood for deciding the spillway capacity of projects located in similar hydro-meteorological regions. Typically during a GLOF, about 15-50 million cubic meter of water along with debris may be discharged causing widespread damage in downstream, in some cases for hundreds of kilometres. One significant GLOF event per decade was recorded to have taken place in Himalayan region during 1950s and by 1990s, it had increased to one event per three years (13). Hence, it has also become necessary to monitor the potentially dangerous glacial lakes at regular interval to map the expansion in size of such lakes upstream of the existing projects and also formation of new lakes in upper mountainous region.

In this study, the simulation model of glacial lake, about 205 km upstream of Dugar HEP in Chenab river basin, has been developed for satellite imagery of both 2014 and 2020 to assess the increment in breach discharge of identified glacial lake just downstream of lake. Consequently, the peak discharge has been routed up to Dugar HEP site. The outcome for the both conditions has been compared to get a holistic view of risk associated and way forward.

2. CASE STUDY

2.1 Description of Study Area

The study area of the present study is the catchment area of Dugar Hydro-Electric Project (HEP) in the Chenab Basin. The Dugar HEP is proposed on the Chenab River in Himachal Pradesh, India. The capacity for Dugar HEP is 449 MW. The diversion site for the project is proposed at Latitude 33°07'05"N and Longitude 76°21'20.7"E. The catchment area at proposed diversion site is 7823 km2. The Chenab River is a major tributary of the Indus Basin. The Chandra and Bhaga Rivers join together to form Chenab river.

2.2 Inventory of Glacial Lakes

The identification of glacial lakes in high mountainous regions of a basin is a tedious task. However many remote sensing methods have been developed in the recent past, that can be used effectively to prepare an inventory of glacial lakes in remote areas like upper reaches of Himalaya. To identify the glacial lakes using remote sensing, satellite images should be free of clouds with minimal ice cover. The preparation of glacial lake inventory includes: (a) Identification of glacial lakes using multispectral imagery by differentiating water and other types of surface, (b) Digitisation of lake boundaries using ERDAS tools, (c) Assigning of a number for digitized polygon boundaries, (d) Calculation of surface area of glacial lakes

2.3 Criticality Analysis

After preparation of inventory of glacial lakes, the potentially dangerous glacial lakes have been identified from the inventory based on the water spread area and various other features related to the glacial lakes. Three glacial lakes having water spread area more than 50 hectare, 01_52H_002, 01_52H_004 and 01_52H_005 (naming as per CWC guidelines), have been selected as potentially dangerous as shown in Figure 1.

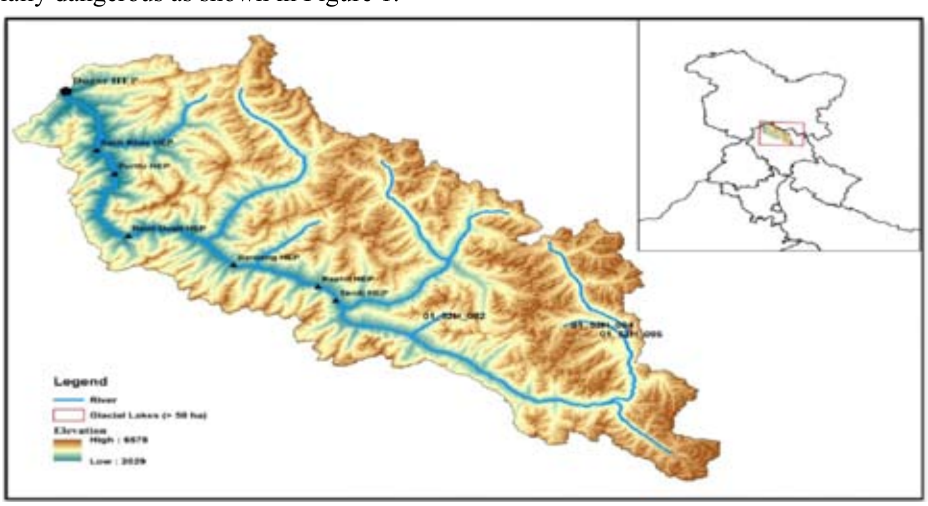

Fig. 1 : Catchment area map of Chenab basin up to Dugar HEP showing potential dangerous glacial lakes and other major planned HEP on Chenab River.

After closely following satellite imagery of 2014 and 2020, it was observed that all of the three glacial lakes have shown an expansion in water spread area. The basic features of these glacial lakes have been given in Table 1. The detailed criticality analysis has been carried out to map out the most critical glacial lake in catchment area of the project and moraine dammed lake 01_52H_004 has found to be most vulnerable. The areal expansion of glacial lake 01_52H_004 has been shown in Figure 2 and Figure 3.

Table 1 : Physical parameters of identified glacial lakes

Lake ID as per CWC Inventory	Longitude	Latitude	Elevation (m)	Area in ha (2014)	Area in ha (2020)	Distance from Dugar HEP (km)	Type
01_52H_002	77°13’06”	33°31’29”	4068	65	105	142	Moraine
01_52H_004	77°32’58”	32°29’55”	4150	88	160	205	Moraine
01_52H_005	77°36’58”	32°28’56”	4275	48	51	202	Cirque

Fig. 2 : Google Earth Image of Glacial Lake 01_52H_004 (2014)

Fig. 3 : Google Earth Image of Glacial Lake 01_52H_004 (2020)

3. MATHEMATICAL MODEL FOR GLOF STUDY

3.1 GLOF- A Dam Break Modelling

GLOF modeling may be treated as a type of dam break unsteady flow modeling. The possible failure mechanism associated with moraine dammed lakes are almost the same as of an earthen dam with difference being only in the time of full breach development. Since the moraine dams are highly porous in nature and have low inherent strength, their breach development time will be small in comparison to a well compacted earthen dam leading near abrupt failure. Further there are two basic parts of a GLOF modeling: (i) Estimation of outburst flood hydrograph just downstream of glacial lake and (ii) Hydrodynamic channel routing of outburst flood to get the GLOF output at a project site through proper attenuation and translation mechanism. For the present study, the MIKE-11 model developed by Danish Hydraulic Institute, Denmark has been used. A typical flow chart of GLOF study has been illustrated in Figure 4.

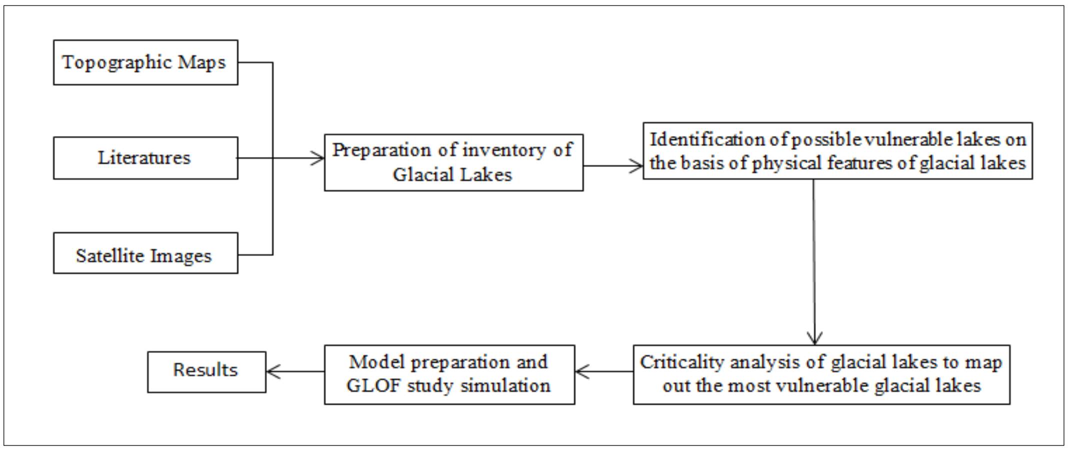

Fig. 4 : Flow Diagram for GLOF Study

3.2 Input Data and Breach Parameters

The depth of the glacial lake and volume of water stored in its reservoir are two primary parameters to estimate GLOF. Different researchers have given different sets of empirical relations to calculate depth and volume. International Centre for Integrated Mountain Development (ICIMOD) guidelines and Christian Huggel's equations are widely used. ICIMOD guidelines provide different average depth for different type of glacial lakes in Bhutan and Nepal (Cirque Lake- 10 m, Lateral Moraine Lake- 20 m, Moraine Lake- 30 m, Blocking Lake and Glacial Erosion Lake- 40 m). The Christian Huggel's equations are developed for moraine glacial lakes in Swiss Alps region, but are being used satisfactorily for glacial lakes of Himalayan regions as well.

$$\textit{Depth}\ (D) = 0.140\mathrm{A}^{0.42}$$

$$\textit{Volume}\ (V) = 0.140\mathrm{A}^{1.42}$$

After criticality analysis, the moraine dammed glacial lake 01_52H_004 (as per CWC Inventory) with estimated volume of 17.6 MCM, located about 205 km upstream of Dugar HE Project diversion site has been adopted to estimate the GLOF. The stream cross sections at an interval of 2 to 5 km, extracted from SRTM DEM, have been utilised to carry out the channel routing in MIKE-11. The Froelich's equations (2007) have been used to determine breach parameters. The glacial lake has been represented by an elevation-area relationship.

4. RESULTS AND DISCUSSION

Satellite images reveal that glacial lake 01_52H_004 has undergone significant areal expansion. In 2014, its surface area was 88 ha (0.088 km2). By the September 2020, the lake area has increased to 160 ha (0.160 km2), showing an increase of approximate 81% relative to 2014. The increase in volume of glacial lake due to increase in water surface area has a direct relation with the resulting GLOF. The consequential increment in outburst flood not only affects the spillway capacity of Dugar HEP, but also various other projects being planned on Chenab River.

Based on the data from satellite imagery of 2014, GLOF peak is found to be 3008 cumec at its origin i.e. just downstream and gets attenuated to 761 cumec at Dugar HEP site for glacial lake 01_52H_004. But based on data of 2020, GLOF peak at its origin increases to 3305 cumec and gets attenuated to 1145 cumec at project site i.e. an increase of about 50% at project site as compared to 2014. The GLOF hydrograph at its origin and at Dugar HEP site for 2014 and 2020 is given in Figure 5 and Figure 6 respectively.

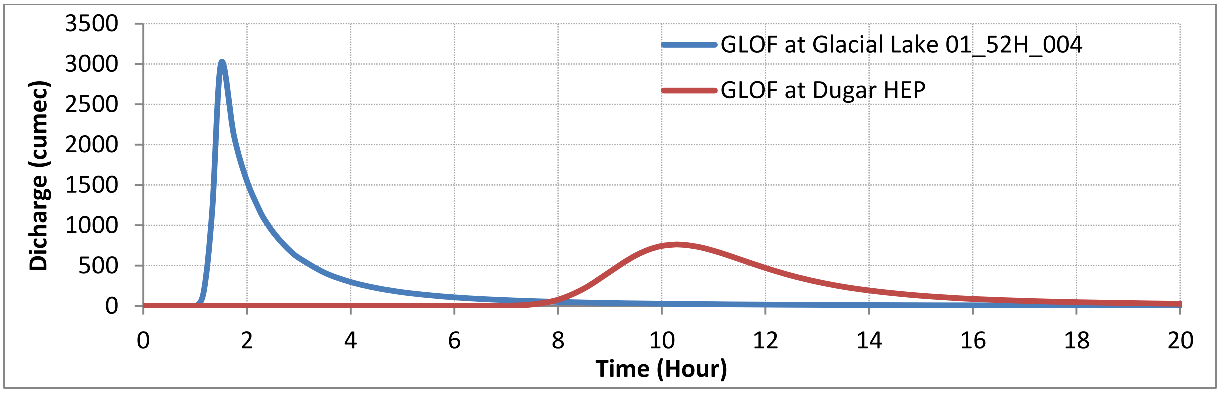

Fig. 5 : GLOF hydrograph at Dugar HEP Site based on 2014 satellite imagery

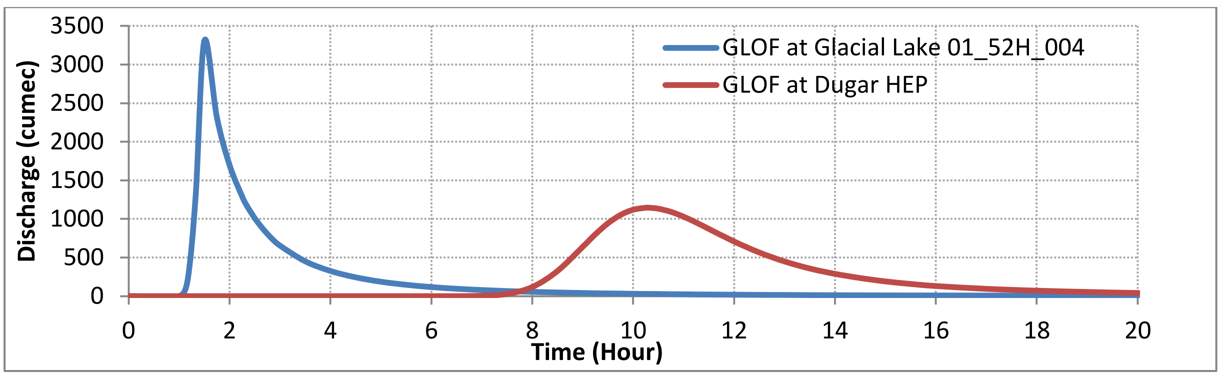

Fig. 6 : GLOF hydrograph at Dugar HEP Site based on year 2020 satellite imagery

5. CONCLUSION

It is an established fact that climate change is severely impacting high mountainous region around the globe and resulting in retreat of glaciers. This phenomenon has increased quite a fold in last few decades resulting in formation of new glacial lakes in river basins and also resulted in expansion of existing lakes. It has raised the risk to existing downstream water resources projects due to more impoundment in reservoir of lakes. Hence, the very first step in minimizing the threat can be to start the monitoring of vulnerable lakes more actively and regularly. The next step would be to carry out detailed studies and model simulation of potentially vulnerable lakes and to share the outcome with the concerned stakeholders. It is also important to closely assess the bathymetric changes of identified lakes, instead relying only on satellite and remote sensing data. It would be helpful to plan any mitigation solutions accordingly. It will reduce the pressure on downstream water resources projects, thus minimising their possibilities of breach.

In the present study, based on the analysis of satellite imagery and simulation of GLOF modeling at Dugar HEP in Chenab basin, it can be concluded that an increase in glacial lake volume may have a disastrous effect on downstream projects in the basin. An increase of 81% in water spread area of glacial lake has led to an increase of 50% in GLOF peak at project site. In this case, two flood events have been selected to carry out GLOF model simulation. The first flood event for the initial conditions of the channel has been taken as average annual flow at respective project site. This condition corresponds to the average flow condition of the river. The second flood event for the initial condition of the river has been taken as 100 year return period flood. The glacial lake outburst may be associated with a flood event. The extent of flood attenuation during hydrodynamic wave approach of channel routing depends on the breach dimension, breach formation time and initial conditions of flow in the entire study reach of the river/channel. Thus, to get reasonable estimate of GLOF at the dam site, the flood due to lake breach needs to be channel routed along with some flood event.

An additional flood cushion may be provided during construction stage of projects to accommodate the increased discharge due to increase in size of glacial lakes. Early Flood Warning System at such potentially dangerous lakes may also be provided to prevent and minimize the flood induced hazards.

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