ENVIRONMENTAL HEALTH | RESEARCH ARTICLE

Glacial lake outburst flood (GLOF) study of Dhauliganga basin in the Himalaya

Lalan Kumar Jha1* and Deepak Khare1

Abstract: Numerous glacial lakes are forming in high-altitude regions worldwide due to rise in temperature. Some of them may burst i.e. Glacier Lake Outburst Flood (GLOF) may occur causing loss of lives, properties and infrastructures in downstream areas. Thus, GLOF study is necessary to understand its threat and save or minimise the imminent losses. In the present study, the highest dangerous glacial lake of Dhauliganga basin in the Himalaya has been considered with a view to estimate the GLOF hydrograph just downstream of the lake and the routed GLOF hydrograph near Dhauliganga Stage-I Dam. The Glacial lake L2 (Latitude 30°26′45″ E and Longitude 80°23′16″ N) is the highest potentially dangerous lake, whose maximum surface area was 132,300 m² acquired on 16 September 2009. GLOF has been simulated for Glacial lake L2 for its maximum volume 2 × 10⁶ m³, by the model prepared with the help of hydraulic software such as HEC-RAS. Results by the model have been compared with the results got by the popular empirical formulae. In average condition, the GLOF hydrograph peak just downstream of Glacial lake L2 is 2,021 cumec and the same is 4,272 cumec in worst condition. The GLOF hydrograph has been routed from Glacial lake L2 to Dhauliganga Stage-I Dam covering a distance around 72 km. In average condition, routed GLOF hydrograph peak near Dhauliganga Stage-I Dam including 100-year return period flood 1,700 cumec is 3,047 cumec at 2 h 01 min and the same is 3,253 cumec at 1 h 46 min in worst condition.

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Received: 06 May 2016
Accepted: 10 October 2016
Published: 31 October 2016

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ABOUT THE AUTHOR
Lalan Kumar Jha is working as a civil engineer in Hydrology unit of Design division of NHPC Ltd since 2002. He wrote the article “Glacial lake outburst flood (GLOF) study of Dhuliganga basin in the Himalaya” during his MTech in IIT Roorkee (2013–2015). As their organisation has been constructing hydropower schemes, his study is focused on examining the safety of dams in case of GLOF event. Nowadays, it is mandatory to conduct GLOF study for safe design of hydropower schemes as well as safety of lives and property in the vicinity. In recent years, frequency of GLOF event has increased and people have become more conscious about change in environment due to construction of hydropower schemes. Therefore, this kind of study has become very essential. Please refer my previous manuscript “Detection and delineation of glacial lakes ...” published by Springer (Jha & Khare, 2016).

PUBLIC INTEREST STATEMENT
Glacial lake outburst floods (GLOFs) may cause loss of lives, as well as the destruction of houses, bridges, fields, forests, hydro-power stations, roads, etc. in the downstream. The recent example of GLOF destruction is Kedarnath disaster in India, which claimed life of thousands of people and caused huge devastation of property and infrastructure in downstream areas. Thus, there is urgent need to carry out GLOF study of potentially dangerous glacial lakes in a basin in order to know magnitude of flood discharge, stage, duration, travel time to the point of interest, etc. to minimise the impending losses. In this manuscript, GLOF study has been carried out to know the flood peak and its travel time for different scenario to assess its impact on Dhauliganga Stage-I Dam and downstream area. The simplified methodology adopted in this study may be employed for studies to be carried at different locations of other basins.
1. Introduction

During twentieth century, greenhouse gases emission into Earth’s atmosphere increased manifold due to incessant use of natural resources especially fossil fuels by human being. This caused increase in surface air temperature globally and the common word coined for it, is “Global warming”. An increase of 0.85°C in surface air temperature has been estimated on the basis of globally averaged temperature data over the period of 1880–2012 (IPCC 5th Assessment Report, 2013 as cited by Che, Xiao, & Liou, 2014). Also, it has been observed that during last three decades, there is warming in the Himalayas around 0.15–0.60°C per decade (Shrestha, Nakagawa, Kawaike, Baba, & Zhang, 2010). Since, glaciers are very sensitive to change in temperature as well as other climatic factors; the life cycle of glaciers in the Himalaya changed considerably. As a result, ice and snow mass of glaciers are melting at faster rate. Consequently, Himalayan glaciers have thinned and receded (Ageta & Kadota, 1992; Fushinmi, 2000 as cited in WWF Nepal Program, 2005) causing formation of a large number of glacial lakes. Further, majority of these glacial lakes have been formed behind loosely consolidated moraine dams which are inherently unstable. These lakes may burst due to triggering by moraine failures induced due to lake area expansion rate, up-glacier and down-valley expansion rate, dead-ice melting, seepage, the degradation of permafrost, a seismic activity, a flood wave caused due to a rock, snow, or ice avalanche into the lake and abrupt rise in the water level due to heavy precipitation (Bolch et al., 2011; Watanae, Lamsal, & Ives, 2009); consequently sudden release of huge reserve of water and debris i.e. glacier lake outburst flood (GLOF) may occur. In most of the incidences, GLOFs transform into flash floods, causing loss of lives, as well as the destruction of houses, bridges, fields, forests, hydro-power stations, roads, etc. in the downstream (Das & Murugesh Prabhu, 2012; Richardson & Reynolds, 2000). At the locations where flow-path is steep & erodible material is available, GLOFs often get converted into even more destructive debris flows (e.g. Clague & Evans, 1992; Clague, Evans, & Blown, 1985; Huggel, Kääb, Haeberli, Teyssière, & Paul, 2002; Kääb et al., 2005; Chiarle et al. 2007 as cited by Petrakov et al., 2007).

Thus, GLOFs pose a serious hazard in populated mountainous regions all over the world (Clague & Evans, 2000; Iwata et al., 2002; Huggel, Kääb, Haeberli, & Krummenacher, 2003; Huggel et al., 2005; Richardson & Reynolds, 2000; Ma et al. 2004 as cited by Bolch et al., 2011). This is more evident from the reports of killing of some 32,000 people by GLOF incidences in Peru during this century; as well thousands of people and livestock have died in the Himalayas in the last 50 years due to catastrophic flash flood generated by outbursts from lakes high in the mountains (Richardson and Reynolds, 2000). Additionally, it has been observed that GLOFs occurrence have become frequent in the Himalayas in recent decades (Bojrabcharya, Mool, & Shrestha, 2006; Iwata et al., 2002; Mool, 1995; Sakai, Chikita, & Yamada, 2000; Walder & Costa, 1996; Wang, Liu, Guo, & Xu, 2008; Xu, 1988 as cited by Yaning, Changchun, Yapeng, Weihong, & Jingshi, 2010). The recent example of GLOF destruction is Kedarnath disaster in the Indian Himalaya, which claimed life of thousands of people and caused huge devastation of property and infrastructure in downstream areas like Gobindghat, Rambara, Sonprayag, Rudraprayag town and several other parts of the Rudraprayag district.

It is necessary to understand threats of GLOF to save or minimise the imminent losses by taking proper mitigation measures and early warning to downstream people (Shrestha & Nakagawa, 2014). Further, understanding threats of GLOF has become necessary for safety of hydropower projects also, as these projects are moving gradually into the High Himalaya due to availability of high head and sufficient discharge (Shrestha et al., 2010). In the present study, the highest dangerous glacial lake of Dhauliganga basin in the Himalaya has been considered with a view to estimate the GLOF hydrograph just downstream the lake and the routed GLOF hydrograph near Dhauliganga Stage-I Dam. Thus, GLOF has been simulated for the highest potentially dangerous Glacial lake L2 for its maximum volume 2 × 10⁶ m³ (Jha & Khare, 2016), by the model prepared with the help of hydraulic software such as HEC-RAS. As cited by Byers, McKinney, Somos-Valenzuela, Watanae, & Lamsal,
2013, “HEC-RAS 1D unsteady flow model (US Army Corps of Engineers Hydrological Engineering Center [USACE], 2010) is the proven model for GLOF scenarios, which is relatively easy to use, has a large user base, an extensive training literature”. HEC-RAS 1D unsteady flow model has been used for GLOFs studies (Cenderelli & Wohl, 2001, 2003; Osti & Egashira, 2009). HEC-RAS (Hydraulic Engineering Center [HEC], 1995) has been used for similar study “Repeated glacial-lake outburst floods in Patagonia: an increasing hazard?” by Dussaillant et al. (2010). As cited by Clayton and Knox (2008) “We used the HEC-RAS step-backwater model to determine the flood discharge through the reach”. Somos-Valenzuela et al. (2015) has also used the HEC-RAS dam breach model for assessing downstream flood impacts due to a potential GLOF from ImjaTsho in Nepal. Also, HEC-RAS has been used for hydraulic simulation study of Kedarnath flash floods by Durga Rao, Venkateshwar Rao, Dadhwal, and Diwakar (2014). HEC-RAS 1-D (St. Venant) has been used for GLOF study of Sagarmatha region (Nepal) by Bajracharya, Shrestha, and Rajbhandari (2007) and also for GLOF study of south-eastern Tibet by Wang et al. (2012) as cited by Worni, Huggel, Clague, Schaub, and Stoffel (2014). Further, Alho and Aaltonen (2008) have shown that one-dimensional modelling of GLOF propagation using HEC-RAS provides results broadly comparable to data derived from more complex two-dimensional simulations. However, it is recognised that there are limitations in using 1D model in that they have greater uncertainty in predicting inundation extent in GLOF-type flows and cannot adequately represent large feature incision in a debris-laden flow (Byers et al., 2013).

2. Study area
Dhauliganga River originates at an altitude of about 5,330 masl in central Himalaya, is a tributary of Kaliganga River. The catchment area of Dhauliganga River considered in this study is above Dhauliganga Dam stage-I (Lat 29°58′42.6″ E and Long 80°34′19.2″ N). This is located in Dharchula subdivision of Pithoragarh district of Uttarakhand state in India. The catchment area is about 1,350 km² and lies between Longitude 80°14′44″ E to 80°44′01″ E and between Latitude 29°57′00″ N to 30°34′11″ E. The location map is shown in Figure 1. Further, the elevation of the catchment varies from 1,350 to 6,750 masl, and the catchment area above 5,000 masl, which may be considered permanent snowline, is around 381.73 km², i.e. 28.8% of total area. Likewise, the catchment area above 4,500 masl is around 696.16 km², which is 51.57% of total area, may be considered snow-bound catchment area.

The river length up to Dhauliganga Dam stage-I is about 93 km, and the average river slope is around 1 in 25 which comprises very steep to moderate slope at several locations. As reported there are some hydropower schemes on this stretch of Dhauliganga River. Among them, Dhauliganga Dam stage-I is the lowest stage with an installed capacity 280 MW and has been considered outlet point in this study.

3. Data used
ASTER DEM data ASTGTM2_N29E079, ASTGTM2_N29E080, ASTGTM2_N30E079 and ASTGTM2_N30E080 have been used to get spatial information like catchment area, elevation, slope, contour, co-ordinates of points, etc.

Cross-sections of the river stretch from Glacial lake L2 to Dhauliganga stage-I dam have been extracted from above-mentioned DEM data at an interval from 500 to 2,000 m using HEC-GeoRAS. The interval has been decided as per variation in shape, size and orientation of cross-sections. Likewise cross-sections of main tributary Dermaganga have also been extracted.

4. Methodology
Hydrologic Engineering Centre’s River Analysis System (HEC-RAS) has been utilised for present (GLOF) study. As per glacial lake’s analysis by remote sensing techniques and image processing and GIS software, using Landsat data from 1972 to 2013, Glacial lake L2 is the highest potentially dangerous lake with its maximum area 132,300 m² on 16 September 2009 (Jha & Khare, 2016); therefore, it has been chosen for setting up the model for GLOF study. Further, representation of Glacial lake L2 has been accomplished by cross-sections extracted from DEM and glacial lake outburst has been
modelled by dam break structure. In addition to that, cross-sections of river reach from Lake L2 to Dhauli Ganga Stage-I Dam have been used in setting up the model. Also, the river cross-sections have been taken up to the highest bank elevation. Since the river reach has 72-km length and has steep slope at several locations, it was very difficult to stabilise the model. To obviate this problem, the model has been operated in following four parts:

- The glacial lake L2 has been breached in the model for GLOF hydrograph.
- GLOF hydrograph has been routed from Lake L2 to 25 km downstream.
- GLOF hydrograph further routed from 25 km downstream to 46 km downstream of Lake L2.
- Hydrograph further routed from 46 km downstream to 72 km downstream of Lake L2 i.e. near Dhauli Ganga Stage-I Dam.

Cross sections of main tributary Dermaganga have also been used in the model for routing 100-year return period flood contribution from its catchment. The schematic diagram of the HEC-RAS model is shown in Figure 2.
Volume of Glacial lake L2 has been worked out by Huggel’s formula,

\[ V = 0.104 A^{1.42} \]  

where \( V \) = volume of lake and \( A \) = surface area of lake.

GLOF event is not very common phenomenon. Additionally, studies on GLOFs and their floods or sediment disasters in downstream areas are very limited (Shrestha et al., 2014). Therefore, breach parameters like breach width and full breach formation time are not fully understood (Jain, Lohani, Singh, Chaudhary, & Thakural, 2012). But we know that modes of failure of Moraine dams are similar to earthen dams as following:

- Both are non-overtopping i.e. they may fail in case of overtopping by flood discharge.
- Both are susceptible to shear stress by water column and may fail after breach development.
- Both may fail due to erosion by wave or series of waves in the lake.
- Both may fail due to excessive seepage.
Several empirical equations are available to predict breach parameters of earthen dam. Also almost all equation use, \( h_w \) which is depth of water above breach invert at time of failure except Froehlich who use \( h_b \) which is height of breach. “\( h_w \)” cannot be estimated without proper knowledge of the actual dam break event whereas in critical condition \( h_b \) may be estimated as height of the dam. Thus in the present study, breach parameters like breach width and full breach formation time have been estimated as per popular empirical equations for Earthen Dam given by Froehlich (Wahl, 2004).

\[
\text{Average breach width (} B_w \text{) in m} = 0.1803 K_o (V_w)^{0.32} (h_b)^{0.19} \tag{2}
\]

\[
\text{Failure time (} T_f \text{) in h} = 0.00254 (V_w)^{0.53} (h_b)^{-0.9} \tag{3}
\]

where \( V_w \) is the volume of water stored above the breach at the time of failure (m³), \( h_b \) is the height of the breach (m), \( K_o = 1.4 \) for overtopping and 1 for piping.
The side slope of breach has been taken as 0.8 h:1 v.

It has been assumed that dam breach occurred due to overtopping and coincided with 100-year return period flood at Dhauliganga Stage-I Dam. Accordingly, 100-year return period flood has been distributed in the catchment as shown in Figure 3 and considered as constant discharge at its respective outlet points to facilitate routing of GLOF hydrograph.

The Manning’s roughness coefficient for mountainous stream with no vegetation, banks usually steep, trees and bushes on the submerged banks, having gravel, cobbles and boulders at bottom, ranges from 0.03 to 0.07 (Chow, 1959 as cited in HEC-RAS Manual HEC, 2010). It is known that Himalayan Rivers have mountainous terrain in upper reaches having gravel, cobbles and boulders at bottom. As well, large debris flow occurs during GLOF and high velocity may erode banks and bottom increasing the sediment load, so range of Manning’s roughness coefficient has been considered from 0.04 to 0.06. Thus, the model has been run for different set of breach parameters and Manning’s “n” 0.04, 0.05 and 0.06 have been utilised to check the sensitivity of the model.

Contraction and expansion coefficient values have been assigned 0.1 and 0.3, respectively, as recommended by the Hydrologic Engineering Center (2010) manual for gradual flow transitions.

5. Results and discussion
GLOF study has been carried out for the highest potentially dangerous lake L2 which has the largest surface area 132,300 m² in September 2009. Using Equation (1),

\[ V = 0.104(132,300)^{1.42} = 1,948,266 \text{ m}^3 \]

Further, breach parameters have been estimated using Equations (2) and (3). Thus, average breach width \((B_w) \) in m = 0.1803 \times 1.4 \times (2,000,000)^{0.32} \times (30)^{0.19} = 50 \text{ m} for overtopping. Whereas, the width of moraine dam of glacial Lake L2 is about 150 m. Therefore, model has been run for 50, 100 and 150 m breach width. Likewise, Failure time \((T_f) \) in hour = 0.00254 \times (2,000,000)^{0.53} \times (30)^{-0.9} = 0.26 \text{ h}. It is known that failure time in case of an earthen dam generally ranges from 0.1 to 1 h. Thus, model has been run for 0.33, 0.50, 0.75 and 1-h breach formation time.

Further, the GLOF hydrograph has been routed from Glacial lake L2 to Dhauliganga Dam Stage-I covering 72-km distance in unsteady flow condition. The results of the model for GLOF in case of breach of Glacial lake L2 are shown in Tables 1 and 2. As per these results, the highest Peak of GLOF hydrograph just downstream of Glacial lake L2 is 4,455 cumecs for breach width = 150 m, failure time = 0.33 h and Manning’s n = 0.04 and the lowest peak of the same is 1,469 cumecs for breach width = 50 m, failure time = 1 h and Manning’s n = 0.06. It has been observed that Manning’s n is not sensitive for GLOF hydrograph at this location.

Hydraulic simulations and empirical models may be combined to overcome some of the limitations imposed by both the lack of knowledge of the breach formation processes and the moraine characteristics (Rivas, Somos-Valenzuela, McKinney, & Hodges, 2014). Thus, in the absence of any other suitable means/information, the popular empirical relations have been used to estimate peak flows for comparison with the results worked out by HEC-RAS simulation to arrive at the reasonable estimate of GLOF.

Popov 1991 (as cited in Huggel, 2002) gave an empirical relation for volume of lake and peak flow of moraine dam,

\[ Q_{\text{max}} = 0.0048 V^{0.896} \]

where \( V = \text{volume of lake in m}^3, \) in present case \( V = 2 \times 10^6 \text{ m}^3 \)

Using above relation, \( Q_{\text{max}} = 0.0048 \times (2,000,000)^{0.896} = 2,123 \text{ cumecs}. \)
Costa and Schuster, (1988) (as cited in Huggel 2002) developed an empirical relation for PE the potential energy of the lake water and peak flow of moraine dam,

\[ Q_{\text{max}} = 0.00013(PE)^{0.60}, \quad (5) \]

where \( Q_{\text{max}} \) is the peak discharge (m³/s) and PE the potential energy of the lake water. PE is the product of dam height (m), lake volume (m³) and the specific weight of water (9,800 N/m³).

In the present case, Lake volume = 2 × 10⁶ m³ and Dam ht. derived from DEM with the help of length of lake (500 m) and slope (0.06) = 30 m (verified by mean depth by Huggel’s formula).

### Table 1. GLOF hydrograph peak just downstream of glacial lake L2

| Failure time | Manning’s “n” | Peak width = 50 m | Breach width = 100 m | Breach width = 150 m |
|-------------|---------------|-------------------|---------------------|---------------------|
|             |               | Peak | Time to peak | Peak | Time to peak | Peak | Time to peak |
| h           |               | cumec | min | cumec | min | cumec | min |
| 0.33        | 0.04          | 3,752 | 14  | 4,275 | 12  | 4,455 | 11  |
| 0.05        | 0.06          | 3,748 | 14  | 4,270 | 12  | 4,448 | 11  |
| 0.5         | 0.04          | 2,691 | 19  | 2,953 | 17  | 3,061 | 16  |
| 0.05        | 0.06          | 2,691 | 19  | 2,951 | 17  | 3,059 | 16  |
| 0.75        | 0.04          | 1,896 | 27  | 2,021 | 24  | 2,076 | 22  |
| 0.05        | 0.06          | 1,895 | 27  | 2,021 | 24  | 2,076 | 22  |
| 1           | 0.04          | 1,469 | 33  | 1,550 | 30  | 1,579 | 28  |
| 0.05        | 0.06          | 1,469 | 33  | 1,550 | 30  | 1,578 | 28  |

### Table 2. Routed GLOF hydrograph peak near Dhauliganga Stage-I Dam i/c 100-year return period flood 1,700 cumec

| Failure time | Manning’s “n” | Peak width = 50 m | Breach width = 100 m | Breach width = 150 m |
|-------------|---------------|-------------------|---------------------|---------------------|
|             |               | Peak | Time to peak | Peak | Time to peak | Peak | Time to peak |
| h           |               | cumec | h:min | cumec | h:min | cumec | h:min |
| 0.33        | 0.04          | 3,472 | 1:33 | 3,487 | 1:31 | 3,478 | 1:30 |
| 0.05        | 0.06          | 3,250 | 1:48 | 3,253 | 1:46 | 3,257 | 1:45 |
| 0.5         | 0.04          | 3,178 | 1:55 | 3,179 | 1:53 | 3,169 | 1:52 |
| 0.05        | 0.06          | 3,033 | 2:09 | 3,038 | 2:07 | 3,029 | 2:06 |
| 0.75        | 0.04          | 3,183 | 1:48 | 3,195 | 1:46 | 3,174 | 1:45 |
| 0.05        | 0.06          | 3,038 | 2:04 | 3,047 | 2:01 | 3,043 | 2:00 |
| 1           | 0.04          | 2,930 | 2:19 | 2,927 | 2:16 | 2,926 | 2:15 |
| 0.05        | 0.06          | 2,993 | 1:57 | 3,010 | 1:53 | 3,010 | 1:52 |
| 0.06        | 2,901 | 2:12 | 2,914 | 2:09 | 2,902 | 2:08 |

In the present case, Lake volume = 2 × 10⁶ m³ and Dam ht. derived from DEM with the help of length of lake (500 m) and slope (0.06) = 30 m (verified by mean depth by Huggel’s formula).
Using above relation, 

\[ Q_{\text{max}} = 0.00013(30 \times 2,000,000 \times 9,800)^{0.60} = 1,498.20 \text{ say 1,500 cumec.} \]

Evans 1986 (as cited in Huggel, 2002) gave an empirical relation between peak discharge and volume of reservoir; the same may also be used for estimating peak discharge as Moraine dam is similar to man-made Earth and Rockfill dam.

\[ Q_{\text{max}} = 0.72V^{0.53} \]  \hspace{1cm} (6)

where \( V \) = volume of lake in \( \text{m}^3 \), in present case \( V = 2 \times 10^6 \text{ m}^3 \)

Using above relation, 

\[ Q_{\text{max}} = 0.72(2,000,000)^{0.53} = 1,573 \text{ cumec.} \]

Huggel (2002) (as cited in Huggel, 2002) gave an empirical relation between peak discharge and reservoir volume for moraine dam

\[ Q_{\text{max}} = 0.00077 \times V^{1.017} \]  \hspace{1cm} (7)

where \( V \) = volume of lake in \( \text{m}^3 \), in present case \( V = 2 \times 10^6 \text{ m}^3 \)
Using above relation $Q_{\text{max}} = 0.00077(2,000,000)^{1.017} = 1,971$ cumec.

The Popov formula is giving the highest value 2,123 cumec. This is nearly matching with the GLOF peak = 2,021 cumec simulated by the model in case of failure time = 0.75 h, breach width = 100 m, Manning's $n = 0.05$ as shown in Figure 4. Therefore, in average condition this case may be considered the realistic estimate of GLOF hydrograph just downstream of Glacial lake L2.

Haeberli’s (as cited in Huggel, 2002) gave a worst-case estimate,

$$Q_{\text{max}} = 2 \frac{V}{t}, \text{ where } t = 1,000 \text{ s (a time constant)}.$$  \hspace{1cm} (8)

Using above relation $Q_{\text{max}} = 2 \times 2,000,000/1,000 = 4,000$ cumec.

This is nearly equal to GLOF hydrograph peak = 4,272 cumec simulated by the model in case of failure time = 0.33 h, breach width = 100 m and Manning's $n = 0.05$ as shown in Figure 4. Therefore, in worst condition this case may be considered the realistic estimate of GLOF hydrograph just downstream of Glacial lake L2.

As concluded earlier, in average condition, corresponding routed GLOF hydrograph peak near Dhauliganga Stage-I Dam including 100-year return period flood 1,700 cumec is 3,047 cumec simulated by the model for failure time = 0.75 h, breach width = 100 m and Manning’s $n = 0.05$ as shown in Figure 5. In worst condition, corresponding routed GLOF hydrograph peak near Dhauliganga Stage-I Dam including 100-year return period flood 1,700 cumec is 3,253 cumec simulated by the model for failure time = 0.33 h, breach width = 100 m and Manning’s $n = 0.05$ as shown in Figure 5.

Among different case of simulation shown in Table 2, the lowest peak of routed GLOF hydrograph near Dhauliganga Stage-I Dam including 100-year return period flood 1,700 cumec is 2,817 cumec for breach width = 150 m, failure time = 1 h and Manning’s $n = 0.06$ and the highest Peak of the same is 3,486 cumec for breach width = 100 m, failure time = 0.33 h and Manning’s $n = 0.04$. The average value of routed GLOF considering all cases is 3,106 cumec. Therefore, GLOF estimate as concluded in earlier paragraphs appears reasonable. Additionally, it has been observed that Breach width is not sensitive for GLOF hydrograph at this location due to routing for about 72 km. Maximum velocity observed during routing in this river stretch varies from 4.5 to 14.75 m/s.

GLOF phenomenon is characterised as sudden release of accumulated water and debris from glacial lake creating flash flood situation in downstream, whereas the model has been operated for clear water condition, therefore the result has its own limitation.

6. Conclusions and recommendations

6.1. Conclusions

HEC-RAS software is freely available for public use, thus very helpful in this type of study. Further, HEC-RAS 1-D unsteady-flow hydraulic model may be used easily to simulate GLOF phenomenon along with routing of GLOF hydrographs to downstream locations. Thus, GLOF hydrographs may be worked out at any desired locations in downstream. Also, in the absence of any field information/data, the results may be validated using empirical relations. In present study, it can be seen that peaks of GLOF hydrographs worked out by the model are consistent with the peaks derived from popular empirical relations.

In average condition, the GLOF hydrograph peak just downstream of Glacial lake L2 is 2,021 cumec simulated by the model for failure time = 0.75 h, breach width = 100 m and Manning’s $n = 0.05$, whereas corresponding routed GLOF hydrograph peak near Dhauliganga Stage-I Dam including 100-year return period flood 1,700 cumec is 3,047 cumec at 2 h 01 min. In worst-condition, GLOF hydrograph peak just downstream of Glacial lake L2 is 4,272 cumec simulated by the model for failure...
time = 0.33 h, breach width = 100 m and Manning’s n = 0.05, whereas corresponding routed GLOF hydrograph peak near Dhauliganga Stage-I Dam including 100-year return period flood 1,700 cumec is 3,253 cumec at 1h 46 min. These values have been arrived at by comparing results of the model with the values derived by well-known empirical formulae. In simulation of GLOF by the model, Manning’s n is not sensitive for GLOF hydrograph at just downstream of Glacial lake L2. It has also been observed that breach parameter like breach width is least sensitive for routed GLOF hydrograph at 72 km downstream from Glacial lake L2 i.e. near Dhauliganga Stage-I Dam.

### 6.2. Recommendations

Following recommendations may improve the result of similar study in future:

- ASTER DEM data which have 30-m spatial resolution have been used for extraction of river cross-sections for preparation of HEC-RAS model for routing of GLOF. High-resolution DEM, which are available commercially/free, are recommended for better result.

- In simulation of GLOF, clear water has been considered in the HEC-RAS model whereas GLOF is always accompanied by debris accumulated in the lake as well as sediment carried along the river. Thus, for simulation of actual GLOF phenomenon, some appropriate software which would be able to consider debris and sediment load also is recommended.

- GLOF phenomena occur in mountainous region worldwide and cause huge devastation of property, infrastructure and lives downstream. Therefore, it is strongly recommended to conduct thorough research for better understanding of GLOF.

### Funding

This work was supported by NHPC Ltd.

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### Citation information

Cite this article as: Glacial lake outburst flood (GLOF) study of Dhauliaganga basin in the Himalaya, Lalan Kumar Jha & Deepak Khare, Cogent Environmental Science (2016), 2: 1249107.

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