# Chapter 4
# Hydrodynamic Modelling of Glacial Lake Outburst Floods

To better understand the impacts that a GLOF can have on the downstream valleys, an attempt was made to simulate one GLOF event each in Nepal and Bhutan using hydrodynamic modelling.[1] The two models are discussed below.

## Modelling a Lake Imja Tsho GLOF

Lake Imja Tsho is an ice core moraine dammed lake that was estimated to cover about 0.94 square km in 2006. The details of the lake are given in Chapter 3. A short review of materials and methods is given below and the main outcomes of the modelling are discussed.

The topographic information needed for the hydrodynamic modelling was derived from topographic maps published by the topographic Survey Department of Nepal in 1996. The digital elevation model (DEM) was derived from 40m interval contour maps and the river valley cross-sections were derived from the DEM. Bathymetric information for the Lake Imja Tsho was derived from the results of the bathymetric survey of 2001 conducted jointly by Glaciological Expedition in Nepal (GEN) and the Department of Hydrology and Meteorology, Nepal (DHM).

The geometric and hydraulic information from the DEM was extracted using the US Army Corps of Engineers (USACE) software HEC GeoRAS v3.1.1. First, the stream centreline was established from the DEM. The banks were digitized based on topographic maps and high-resolution IKONOS imageries. The GLOF simulation encompasses the entire area from the outlet of the lake and terminating at the boundary of the Dudh Koshi basin buffer zone. The length derived for the Lake Imja Tsho GLOF simulation was 45.22 km. River cross-sections were established at 200m intervals, a total of 209 cross-sections. The cross-sections used were about 1700m wide since this is the maximum HEC GeoRAS width for the DEM resolution used. AutoCAD was used to automatically delineate the cross-section lines at regular intervals. In a few cases, the automatically delineated cross-section lines had to be manually edited because they overlapped each other where there was a sharp meander in the streamline.

### Dam breach model

A dam breach model developed by the National Weather Services (NWS-BREACH) was used to simulate the outburst hydrographs. The inputs required by this model include the geometry and some geotechnical parameters of the moraine dam, the lake area, and the lake depth information. The geometric data of the Dig Tsho moraine dam were taken from the DEM. Since geotechnical parameters for the lakes were not available, parameters from the Tsho Rolpa were used (DHM 1996). This substitution is justified because of the many similarities

[1] Contributed by B. Bajracharya, A.B. Shrestha, L. Rajbhandari, P.R. Maskey, and S.P. Joshi

Table 4.1: **Parameters and input data for NWS-BREACH model for Lake Imja Tsho**

| Parameter | Value |
|---|---|
| Lake surface area | 0.86 $km^2$ |
| Lake maximum depth | 90m |
| Dam top altitude | 5030m |
| Dam bottom altitude | 4960m |
| Dam inside slope | 1:06 |
| Dam outside slope | 1:08 |
| Dam width | 600m |
| Dam length | 650m |
| $d_{50}$ | 1 mm |
| $d_{90}$ | 300 mm |
| $d_{30}$ | 0.1 mm |
| $d_{90/30}$ | 3000 |
| Unit weight | 2000 kg $m^{-3}$ |
| Porosity | 0.4 |
| Manning's n of outer core of dam | 0.15 |
| Internal friction angle (ø) | 34 |
| Cohesion | 0 |

between the two cases. Geometric data of the moraine dam of Lake Imja Tsho was based on information from a detailed survey conducted by Japanese scientists (Watanabe 1995) and the lake area-depth information was based on the bathymetric data of the lake (GEN 2001). Some parameters and important data used in the NWS-BREACH model are given in Table 4.1.

After the GLOF hydrograph was derived from the NWS-BREACH model, the nature of flood propagation in the downstream was derived from hydrodynamic modelling. For this, the geometric and hydraulic data from HEC GeoRAS was exported to HEC-RAS, a single dimensional hydrodynamic model developed by the US Army Corps of Engineers, Hydrologic Engineering Center (HEC) (USACE 2004). A flow hydrograph, derived from NWS-BREACH, was given as the upstream boundary. The downstream boundary condition was given as a discharge rating curve. The discharge rating curve was derived by the Slope-Area method using Manning's equation for open channel flow. For this, the last two cross-sections were used. AutoCAD was used to calculate the channel width, area, and wetted perimeter at different water levels, necessary for the Slope-Area computation.

Although HEC-RAS was able to simulate the flow at steady flow conditions, it could not simulate the unsteady flow conditions due to instability in the model. Even after discussion with the constructors, it was not possible to resolve the problem, probably because of the extremely steep river slope. As simulating the unsteady river flow was essential to predict the GLOF outflow, another model was needed. A one-dimensional hydrodynamic model developed by the National Weather Services U.S.A. (NWS-Flood Wave) was used. This model demands very detailed and elaborate configurational inputs, in terms of model parameters, input data, geometric information, and others. The modelling was performed using 42 cross-sections re-sampled at about 1000m intervals. Although the simulation completed successfully, it was noted that attempts to increase the number of cross-sections prevented the model from converging – most probably due to rapid contraction and expansion.

While NWS-Flood Wave successfully simulated the GLOF, its outputs were limited to numeric results and line-graphs. Additional simulations are required to generate flood maps. The numeric outputs of NWS-Flood Wave were fed into the HEC-RAS model that was set up to run under steady flow conditions. All the cross-sections from the NWS-Flood Wave were used as flow change points in HEC-RAS. The peak discharges at these cross-sections, calculated by NWS-Flood Wave, were used as the flow inputs for the respective points. The unsteady flow was calculated with 209 cross-sections initially derived for the HEC RAS simulation. This resulted in relatively smooth high flood levels along the river reaches. The high flood level data for all cross-sections were exported back to HEC Geo-RAS, which has an in-built internal algorithm to generate inundation and flood depth maps.

## Results of hydrodynamic modelling

For this study, only one scenario of dam breach was considered; the GLOF hydrograph is shown in Figure 4.1. The outputs of the dam breach produced using NWS-BREACH are given in Table 4.2; The rather long predicted duration of the outflow is most probably due to the width of the Lake Imja Tsho moraine dam.

The peak flow and maximum flood depth along the river reaches are shown in Figure 4.2. The attenuation of Lake Imja Tsho GLOF is much dampened. The peak discharge of 5400 $m^3s^{-1}$ at the outlet of the lake is sustained for a considerable distance. Note that for up to 30 km from the lake (16 km from the boundary of the Dudh Koshi basin) the peak flow attenuation still follows a convex curve. This remarkably sustained peak flow along the reach is attributed to the relatively spread-out outflow hydrograph.

Figure 4.2, bottom, shows the high-flood depth along the rivers. Many closely spaced peaks are found throughout the river reaches. Higher flooding depths occur at the narrower river sections. Such narrow sections can be found at the gorges downstream of Tengboche and upstream of Namche Bazar, and at the confluence of the Dudh Koshi and Bhote Koshi.

The spatial distribution of the flood was analysed by preparing inundation maps for the high flood level along the

**Table 4.2: Main outputs of NWS-BREACH for Lake Imja Tsho**

| Output | Value |
|---|---|
| Maximum outflow ($Q_{max}$) | 5463 $m^3s^{-1}$ |
| Duration of outflow ($T_{out}$) | 3.2 hr |
| Initial water level | 5030.6m |
| Final water level | 4982.3m |
| Final depth of breach | 65.2m |
| Final width of top of breach | 30.5m |

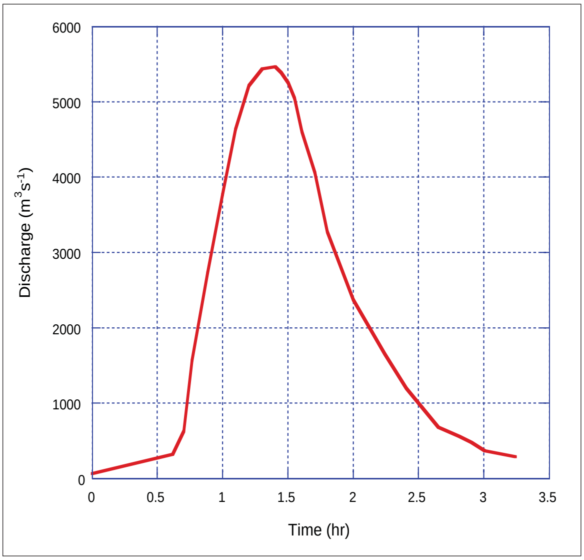


**Figure 4.1:** GLOF hydrograph of Lake Imja Tsho produced using NWS-BREACH

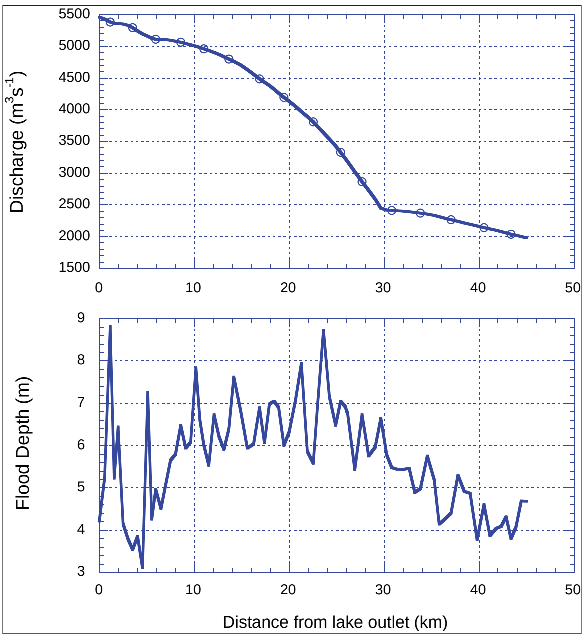


**Figure 4.2:** Estimated peak flow (top) and high flood depth (bottom) in the river

Table 4.3: **Estimated flood arrival time and discharge from Imja GLOF**

| Place | Chainage (km) | Time (min) | Discharge ($m^3s^{-1}$) | Flood depth (m) |
|---|---|---|---|---|
| Imja lake outlet | 0.0 | 0.0 | 5461 | |
| Dingboche | 7.52 | 13.9 | 5094 | 5.8 |
| Orso | 11.55 | 18.8 | 4932 | 5.5 |
| Pangboche | 13.65 | 21.3 | 4800 | 7.6 |
| Larja Dovan (confluence) | 25.94 | 34.8 | 3223 | 6.9 |
| Bengkar | 29.67 | 38.8 | 2447 | 6.6 |
| Ghat | 34.56 | 46.4 | 2355 | 5.8 |

river. The inundation maps reveal the spatial extent of the flooding as well as the depth of the flooding along the river reach (Table 4.3). This table helps estimate the arrival time of the flood – information that can be useful in preparing to reduce the GLOF risk. Simulated inundation maps for the Lake Imja Tsho GLOF are shown in Figure 4.3.

### Limitations

The cross-sections and longitudinal profiles of the stream were derived from a 5m resolution DEM generated from 40m interval contour maps. The DEM, although fine in resolution, cannot capture all the intricacies of the topography and often leads to erroneous results. The accuracy of geotechnical and hydraulic data all contribute to the accuracy of the model; since in this study, all of the model parameters were either estimated or taken from similar studies, the resultant model can continue to be improved as improved geotechnical field data become available. Another limitation is that only a single scenario was considered for each GLOF simulation. Ideally, a systematic sensitivity analysis is first needed to identify the most sensitive parameters; subsequently, several outburst flood routing scenarios should be considered.

## Modelling a Lake Raphstreng Tso GLOF

The topographic information for the model was obtained from 1 inch to 1 mile topographic maps. The cross-sections for the dam break model were prepared from the topographic map for the area, which extends from Lake Raphstreng Tso to Hebesa-Dema for a length of about 115 km and includes the Punakha settlement 84.9 km downstream (Table 4.4). The river valleys were classified into three types based on the width of the cross sections: wide (>500m), medium (260–500m), and narrow (<260m). Typical cross-sections with high flood levels are given in Figure 4.4.

Based on topographic maps, Lake Raphstreng Tso occupied an area of 0.15 $km^2$ in 1960, which by 1986 had expanded to 1.65 km (maximum length) x 0.96 km (maximum width) and had become 80m deep (Sharma et al. 1986). The Indo–Bhutan Expedition of 1995 reported continued expansion, and recorded dimensions of 1.94 km x 1.13 km with a depth of 107m. In 2001, the lake area was 1.23 sq.km (Table 3.8), with an estimated volume of 20.3 million cubic metres (Table 4.5).

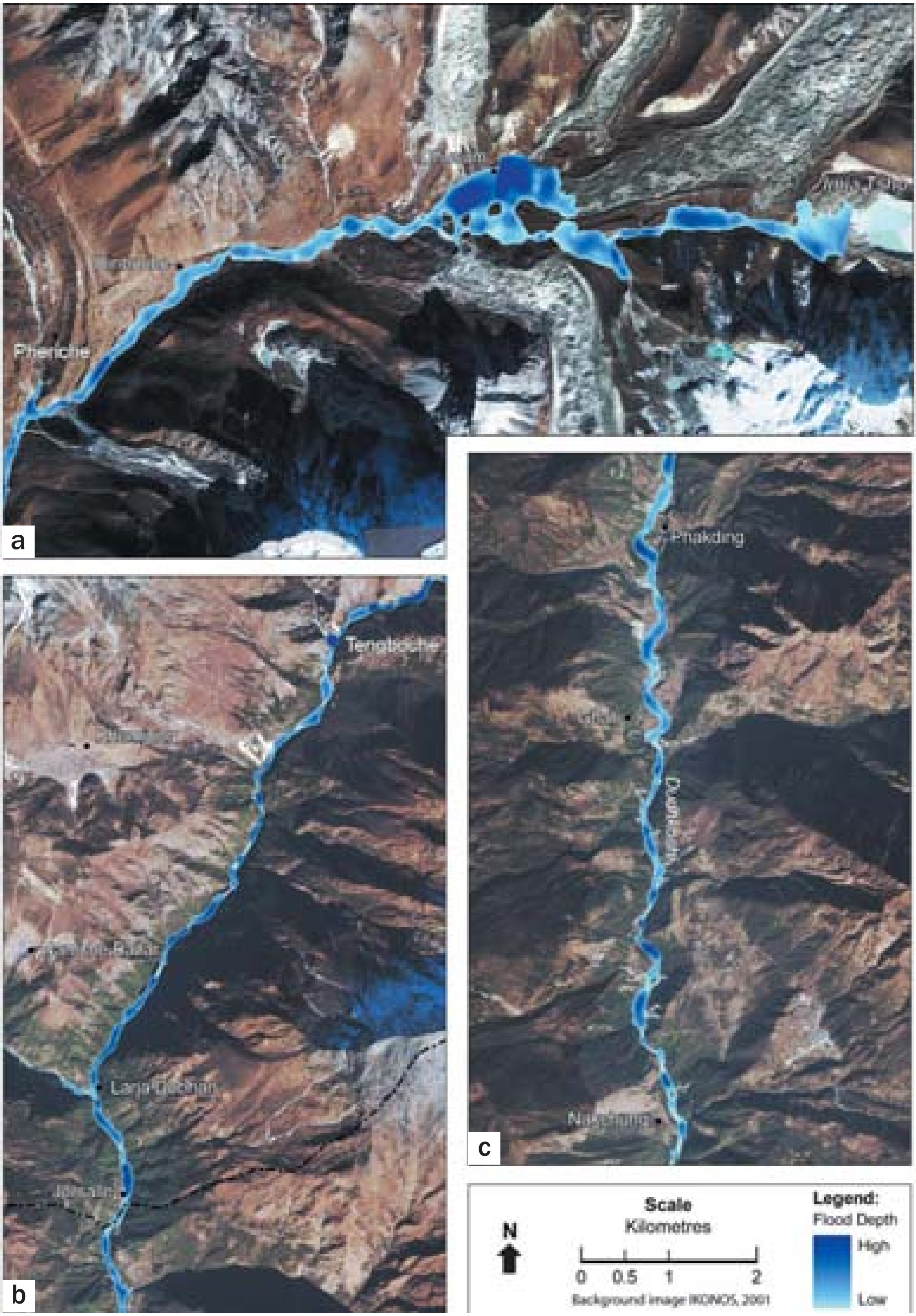


**Figure 4.3:** GLOF hazard in the Imja Khola, Bhote Koshi, and Dudh Koshi valleys obtained from NWS-BREACH. It depicts stretches between Imja Tsho and Pheriche (a), Tengboche and Jorsalle (b), and Phakding and Nakchung (c)

Table 4.4: **Valley cross-sections downstream of Lake Raphstreng Tso classified according to valley width**

| Valley width (m) | Cross-section | Distance from lake outlet (km) | Location | Top width (m) | Avgerage Top width (m) |
|---|---|---|---|---|---|
| Wide (>500) | Lake | 0.0 | Lake | | 1030 |
| | X_Section 1 | 2.6 | | 1145 | |
| | X_Section 2 | 9.9 | | 1231 | |
| | X_Section 10 | 84.9 | Nanikha near the Punakha | 839 | |
| | X_Section 11 | 94.7 | Yuesakha-Bewakha | 903 | |
| Medium (260 – 500) | X_Section 3 | 18.1 | | 405 | 380 |
| | X_Section 7 | 55.4 | Giangkha-Chhuna | 417 | |
| | X_Section 9 | 74.7 | Masepokto-Byaphu | 413 | |
| | X_Section 12 | 104.3 | Hebesa- Dema | 408 | |
| | X_Section 13 | 114.3 | Hebesa-Dema | 359 | |
| Narrow (<260) | X_Section 4 | 28.1 | | 172 | 221 |
| | X_Section 5 | 37.9 | | 238 | |
| | X_Section 6 | 46.1 | | 218 | |
| | X_Section 8 | 64.6 | After the Ya Chhu River | 255 | |

Table 4.5: **Lake surface area and storage volume of Lake Raphstreng Tso**

| **Altitude (m)** | 4360 | 4340 | 4320 | 4300 | 4280 | 4260 | 4240 | 4236 |
|---|---|---|---|---|---|---|---|---|
| **Surface area (sq. km)** | 1.018 | 0.821 | 0.667 | 0.391 | 0.119 | 0.023 | 0.003 | 0.000 |
| **Volume (million $m^3$)** | 20.353 | 16.412 | 13.331 | 7.829 | 2.324 | 0.412 | 0.0108 | 0 |
| **Volume used in model (million $m^3$)** | 20.353 | | | | | | | |

## Dam breach model

A dam breach model developed by the National Weather Services (NWS-BREACH) was used to simulate the outburst of the moraine dammed Rapshtreng Tso glacial lake in order to simulate the GLOF hydrographs. The model requires inputs of field data; these data were gathered in part from topographical maps, from reports (Skuk et al. 2002; Yamada and Naito 2003) and from educated guesses of what might be reasonable, based upon extensive experience in the field. Important input parameters for the NWS-BREACH Model are given in Table 4.6

After the GLOF hydrograph was derived from the NWS-BREACH model, the nature of the flood propagation in the downstream areas was modelled hydrodynamically using the flood wave propagation model of National Weather Services (NWS-Flood Wave). The flow hydrograph derived from NWS-BREACH was used as the upstream boundary condition, and the downstream boundary condition was given as the discharge rating curve.

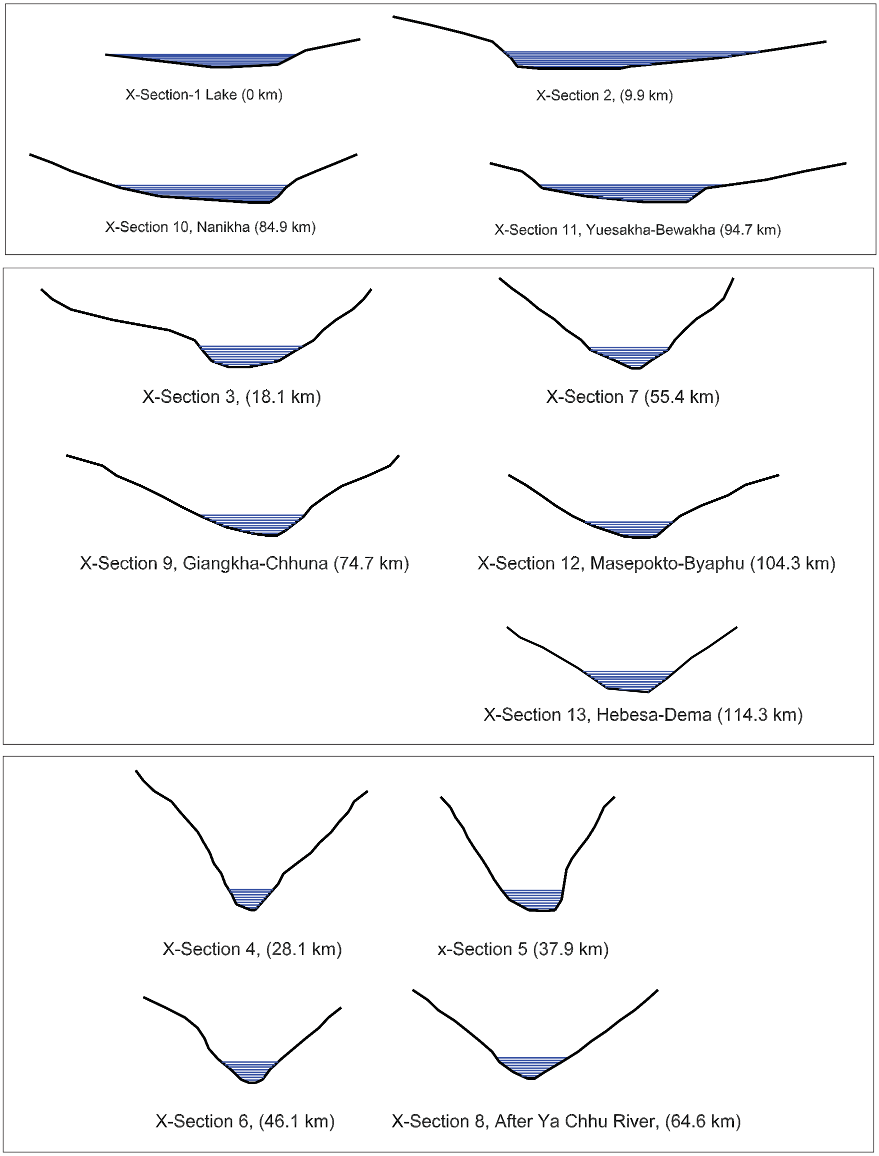


**Figure 4.4:** Typical cross-sections of the Pho Chu River valley

## Results

The breach flow hydrograph is derived from the NWS-BREACH model, considering breach heights of 9 to 56m. The breach height of 56m is the maximum depth of breach corresponding to the characteristics of Lake Rapshtreng Tso as defined in the NWS-BREACH model. The breach peak flood simulated at the outlet for the maximum breach depth is 5450 $m^3/s$. The GLOF hydrographs for different breach heights from 9 to 56m show the magnitude of breach flow for different scenarios (Figure 4.5). The important output parameters derived from THE NWS-BREACH model are given in Table 4.7.

**Table 4.6 Parameters and input data for NWS-BREACH model for Lake Raphstreng Tso**

| Parameter | Value |
|---|---|
| Lake surface area | 1.018 $km^2$ |
| Lake maximum depth | 107m |
| Dam top elevation | 4360m |
| Dam bottom elevation | 4304.3m |
| Dam inside slope | 1:06 |
| Dam outside slope | 1:08 |
| Dam width | 1.13 km |
| Dam length | 1.94 km |
| $d_{50}$ | 1 mm |
| $d_{90}$ | 333.3 mm |
| $d_{30}$ | 0.1 mm |
| $d_{90/30}$ | 3333 |
| Unit Weight | 2100 kg $m^{-3}$ |
| Porosity | 0.41 |
| Manning's n of outer core of dam | 0.08 |
| Internal Friction Angle (ø) | 32 |
| Cohesiveness | 0 |
| Source: Skuk et al. 2002; Yamada and Naito 2003 | |

A breach flow of 5450 $m^3s^{-1}$ (for a maximum breach depth of 56m) is the maximum breach peak flow that can be propagated to downstream of the river valley in this model. The attenuation of this peak flow and the corresponding maximum flood depth along the river reaches is shown in Figures 4.6 and 4.7. The peak discharge at breach is 5450 $m^3s^{-1}$ but decreases sharply to 3000 $m^3s^{-1}$ within the first 10 km stretch, after which it remains stable for the next 30 km. About 40 km downstream the peak flood once again decreases sharply to a value of 500 $m^3s^{-1}$ and becomes even lower over the next 50 km.

Figure 4.7 shows the peak flood depth along the rivers. Peak flood heights of 4m, 3m and 2m occur at 30 km, 40 km and 65 km downstream of the breach. However, the flood height at the Punakha settlement is estimated to be less than 1m due to rapid flood attenuation. The peak flow curves are irregular because of the large time and distance steps; as a result, some peaks might have been missed. Nevertheless, decreasing the size of either the time or the distance steps was not possible since this exceeded the storage capacity of the model.

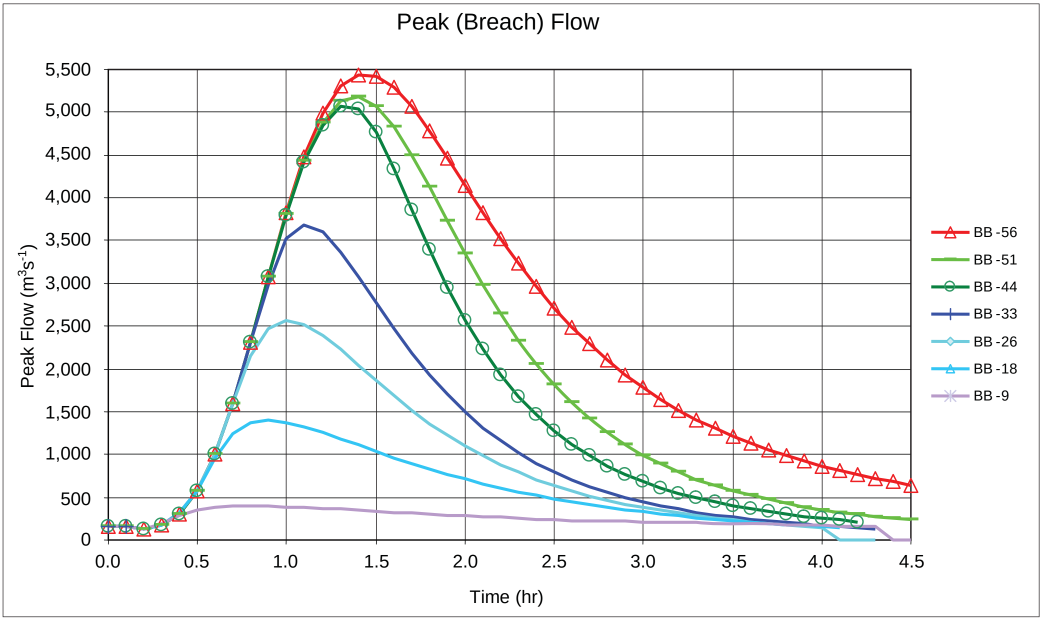


**Figure 4.5:** Lake Raphstreng Tso GLOF hydrograph obtained using NWS-BREACH

Table 4.7: **NWS-BREACH output for various breach heights (Bh=56m to Bh=9 m)**

| Output summary | Bh=56 | Bh=51 | Bh=44 | Bh=33 | Bh=26 | Bh=18 | Bh=9 |
|---|---|---|---|---|---|---|---|
| Max outflow ($m^3s^{-1}$) through breach | 5450 | 5183 | 5084 | 3683 | 2571 | 1399 | 400 |
| Time (hr) at which peak outflow occurs | 1.44 | 1.38 | 1.32 | 1.10 | 1.00 | 0.91 | 0.78 |
| Final depth (m) of breach | 55.65 | 51.25 | 43.89 | 32.53 | 25.72 | 17.94 | 9.14 |
| Top width (m) of breach at peak breach flow | 93.93 | 90.09 | 86.91 | 67.96 | 56.17 | 41.88 | 23.82 |
| Elevation (m) of top of dam | 4360 | 4360 | 4360 | 4360 | 4360 | 4360 | 4360 |
| Final elevation (m) of reservoir water surface | 4313.6 | 4314.3 | 4321.3 | 4331.4 | 4338.4 | 4346.3 | 4354.7 |
| Final elevation (m) of bottom of breach | 4304.3 | 4308.7 | 4316.1 | 4327.4 | 4334.2 | 4342.0 | 4350.8 |
| Side slope of breach (m/m) at peak breach flow | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Bottom width (m) of breach at peak breach flow | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |

Note: Bh indicates breach height

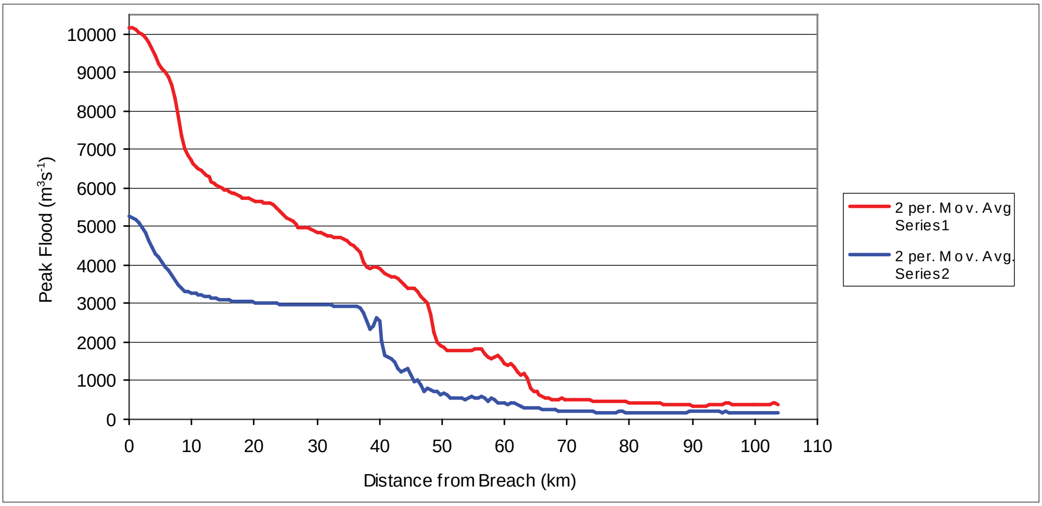


**Figure 4.6:** Peak flood attenuation scenarios in a worst-case flood, and a maximum breach for a possible Lake Raphstreng Tso GLOF in the Pho Chu valley

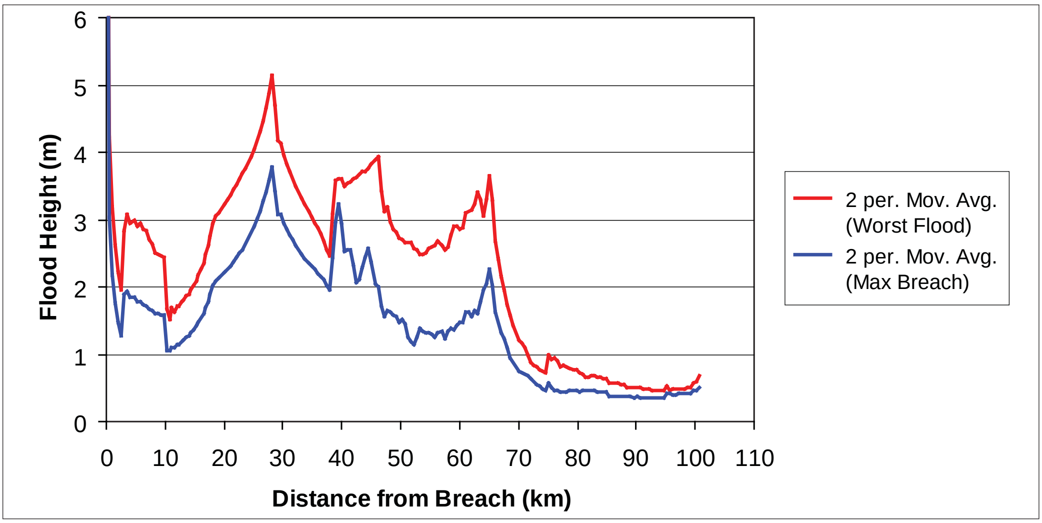


**Figure 4.7:** Peak flood height scenarios in a worst case flood and a maximum breach for possible Lake Raphstreng Tso GLOF in the Pho Chu sub-basin

The peak flood is rapidly attenuated downstream of the valley from the breach. In the wide portions of the valley (<10 km) the peak flood height is less than 2m, and beyond this it reduces further to less than 1m at distances of 85 to 95 km downstream. In medium width portions of the river valley (18.1 and 55.4 km) the peak flood height is 1-2m, reducing to less than 1m at 104 km. The maximum peak flood heights occur mostly in the narrower portions of the river valleys (at 28.1, 37.9, 46.1 and 64.6 kms) where distinctive peaks (2 to 4m in height) can be seen (Figure 4.7).

## Scenario for worst-case peak flow

The NWS-BREACH model estimates a maximum breach height of 56m and peak breach flood of 5450 $m^3s^{-1}$ based on the input parameters used. Some of these parameters had to be estimated, and could possibly have resulted in an underestimation of the peak breach flood. In light of the possible underestimation of the peak breach flood, it was thought prudent to double this number to 10,161 $m^3s^{-1}$ in order to estimate a worst-case scenario for a catastrophic downstream flood. This worst-case peak flood scenario was used to evaluate the impacts of such tremendous magnitude (Figure 4.6 and 4.7). The peak flow (10,161 $m^3s^{-1}$) is sharply attenuated to 7000 $m^3s^{-1}$ within the first 10 km of the lake outlet and continues to be more gradually attenuated to 2000 $m^3s^{-1}$ within 50 km, finally diminishing to 500 $m^3s^{-1}$ at 65 km and further downstream (Figure 4.8).

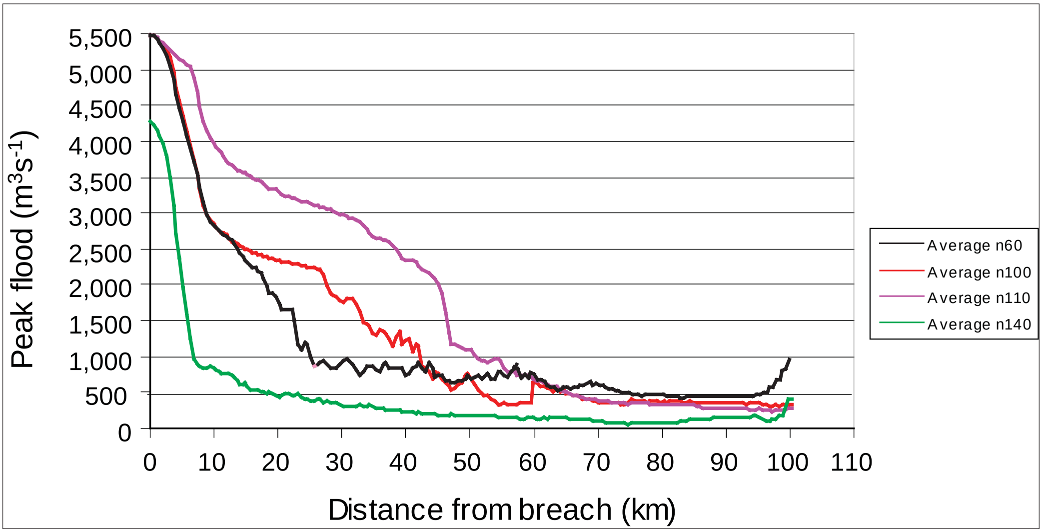


**Figure 4.8:** Variation of peak flow with Manning's 'n' in the Pho Chu sub-basin

The worst-case peak flood is also rapidly attenuated downstream of the valley from the breach. The wide valley (<10 km) has a peak flood height less than 3m, which further reduces to less than 1m between 85 and 95 km. The medium river valley (18.1 km, 55.4 km) has a peak flood height of less than 3m, which reduces to less than 2m at 104 km. The maximum peak flood heights appear mostly in the narrow river valleys (28.1 km, 37.9 km, 46.1 km, and 64.6 km) where distinctive peaks of 4-5m heights can be reached (Figure 4.7). Note that even in a worst-case flood, with a peak flood over 10,000 $m^3s^{-1}$, the GLOF is not likely to directly hit settlements such as Punakha.

## Effect of variation of Manning's 'n'

The Manning's roughness coefficient 'n' determines the sub, super or critical flow condition that determines the flood height. The 'n' value was taken to be 0.08 for the lake outlet and 0.036 for all other reaches – both for the NWS-BREACH model and for the Flood Wave Model. Figure 4.8 shows how a variation in 'n' affects both the peak flood and the maximum flood height. When 'n' increases by 10 per cent, the breach outflow does not change but the downstream peak flood value continues to increase for up to 60 km beyond the lake outlet. When 'n' increases by 40 per cent, a significant decrease occurs in the breach outflow as well as in the downstream peak flood value throughout the downstream valley. When 'n' is decreased by 40 per cent, the breach outflow remains constant until 10 km from the lake outlet. The peak flood value decreases significantly between 10 and 50 km reach but remains almost the same after that.

Similarly, the flood height increases throughout the downstream when the 'n' value is increased by 10 per cent. However, both increasing and decreasing 'n' by 40 per cent have the same effect – the flood height decreases within 65 km from the lake outlet (Figure 4.9). Beyond 65 km from the lake outlet, changes in the value of 'n' have no significant effect.

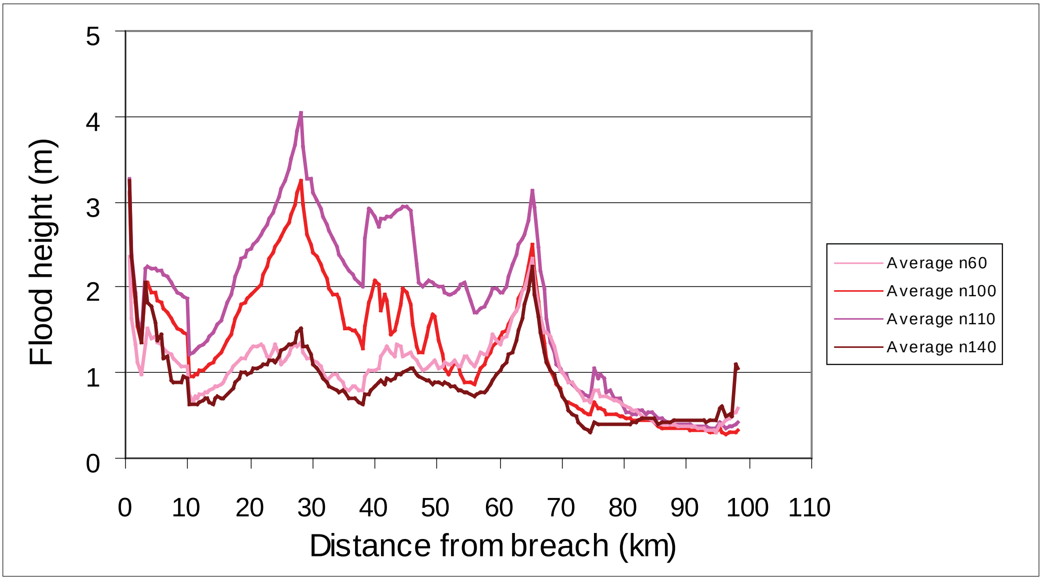


**Figure 4.9:** Variation of flood height with Manning's 'n' in the Pho Chu sub-basin

## Limitations

While modelling can predict peak flood values, these results can be misleading because the impact of secondary processes can often be as devastating as the impacts of high floods. For example, the Lake Luggye Tso, which is adjacent to Lake Raphstreng Tso and similar to it in many ways, suffered a GLOF event in 1994. This model might have predicted that settlements downstream of the breach, where the peak flood value was only about a meter or so, should have been safe. However, the model cannot capture the extent of erosion processes and downstream sedimentation, which are highly dependent on local conditions such as gradient, curvature of the river, valley width and river depth, geomorphology, and so on. What happened on site was that erosion and sedimentation of the river valley continued very far downstream from the breach (Chapter 2, Figure 2.9). The Punakha settlement (containing the religious shrine of Punakha Dzong), which lies about 85 km downstream, was seriously devasted, not by the flood itself but by these secondary events.

In this study, the topographical information (cross sections and longitudinal profile of the stream) were derived from a 1 inch to 1 mile topographical map; other geo-technical parameters were either taken from reports or were based on suitable assumptions. The results of the modelling based on these parameters are preliminary and subject to change as more field-based data becomes available. To run successfully, the model requires that the time and distance steps used be 'small' and that many cross sections be used at the transition of very narrow and wide sections. Limitation in storage capacity arises when small time steps are used but larger time steps can not capture peaks and also prevent the model from converging.

GLOF hazard maps, based on the hydrology and morphology of the river, and which integrate the geomorphology of both of the river and of the vicinity, should be made available to people planning development work in the Pho Chu sub-basin. The possibility of upstream GLOF events must be taken into consideration at the design stage to minimise damage. Vulnerability maps need to be prepared to help anticipate the impacts of GLOFs so that mitigation work can be undertaken.