

GLACIAL LAKE OUTBURST FLOODS IN THE NEPAL HIMALAYA

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ABSTRACT

Glacial lake outburst floods (GLOFs) are a major hazard in high-mountain areas such as the Himalayas of South Asia. As climate change causes glaciers to recede, lakes are left in their wake, held in place by unstable moraines that act as natural dams. Catastrophic events, such as an avalanche into the lake, could trigger a GLOF-causing wave and result in anything from minor erosion to total failure of these moraines. Previous studies of potential GLOFs at Imja Tsho in eastern Nepal have focused on either dam breaching or general disregard for sediment and debris transport. This study attempts to find a middle ground, taking into account debris transport without assuming automatic moraine failure. While these results are preliminary, they nevertheless bring up important issues on the mechanics of the terminal moraine and the comparative usefulness of geographic information systems (GIS) versus field data in assessing GLOFs. This study will serve as an introduction to a future paper to be published by the end of 2017.

INTRODUCTION

The Hindu Kush – Himalaya Region contains more glacial ice and perennial snow than any other region on earth outside the polar regions, and supplies water via its rivers to nearly a quarter of the earth's population (ICIMOD 2011). While much of this ice, upon thawing each spring, reaches these rivers, some remains trapped in lakes and ponds located in remote valleys. Nearly all the glacial lakes of Nepal are held in place by natural moraine dams, which are inherently unstable (Rana *et al.* 2010). Catastrophic events, such as an avalanche, could cause tsunami-like waves that could overtop these moraines and trigger a glacial lake outburst flood (GLOF). The ensuing GLOF could have a devastating impact on both property and human lives downstream. Climate change is exacerbating glacial retreat, making a major calving event more likely (Benn *et al.* 2012).

Among the most studied lakes of Nepal is Imja Tsho, highlighted because of its relatively large population downstream. The village of Dingboche, about 8 km downstream of the lake, houses about 200 people and would be put in serious danger if a GLOF were to be triggered. Numerous studies have attempted to assess the risk and hazard of various lakes in the area. While Imja Tsho is currently listed as a moderate risk, it is expanding quickly up-glacier—within range of an avalanche—and will eventually be classified as a very high hazard (Rounce *et al.* 2016). Future predictions of the lake extent and bathymetry, then, must be taken into account when assessing a GLOF.

This report presents the initial findings of a GLOF model, which is used to map potential inundation areas near Dingboche in order to provide recommendations on the lowering of the lake. Data is taken from both external sources and from field data collected by the research team of Daene McKinney, PhD. While time constraints limit the amount of data and results that can be presented in this report, it is the hope of the research team to have a complete study published within the year.

METHODS

Three primary programs were used for this study. ArcGIS Pro (ESRI, © 2016) was the main application for gathering and processing geographic data, and for depictions of flood results. RAMMS (Rapid Mass Movement Simulation, WSL Institute for Snow and Avalanche Research SLF, © 2016) was used to model an avalanche-generated inflow hydrograph into the lake. BASEMENT (ETH Zurich, © 2016) was used for flood modeling. In addition, QGIS, a free GIS software, was used as preprocessing for the flood model because of its built-in plugin to create BASEMENT-readable meshes. All programs required substantial GIS data, hence they are included in this report.

PREPROCESSING WITH ARCGIS

ArcGIS Pro was the primary program used for preprocessing data. Elevation data for all input models was created from a combination of satellite-generated digital elevation models (DEMs) and field data on the bathymetry of Imja Tsho. First, an 8 meter DEM of the region was merged with the bathymetry using the Mosaic to New Raster tool, assuming a lake elevation of 5007 meters MSL. Next, holes in the DEM were filled using Raster Calculator, incorporating Focal Statistics to interpolate values with no data. Finally, a soil and terrain database (SOTER) provided by ISRIC was used to determine soil types and land cover in the region. The completed DEM with soil data is presented below, in Figure 1.

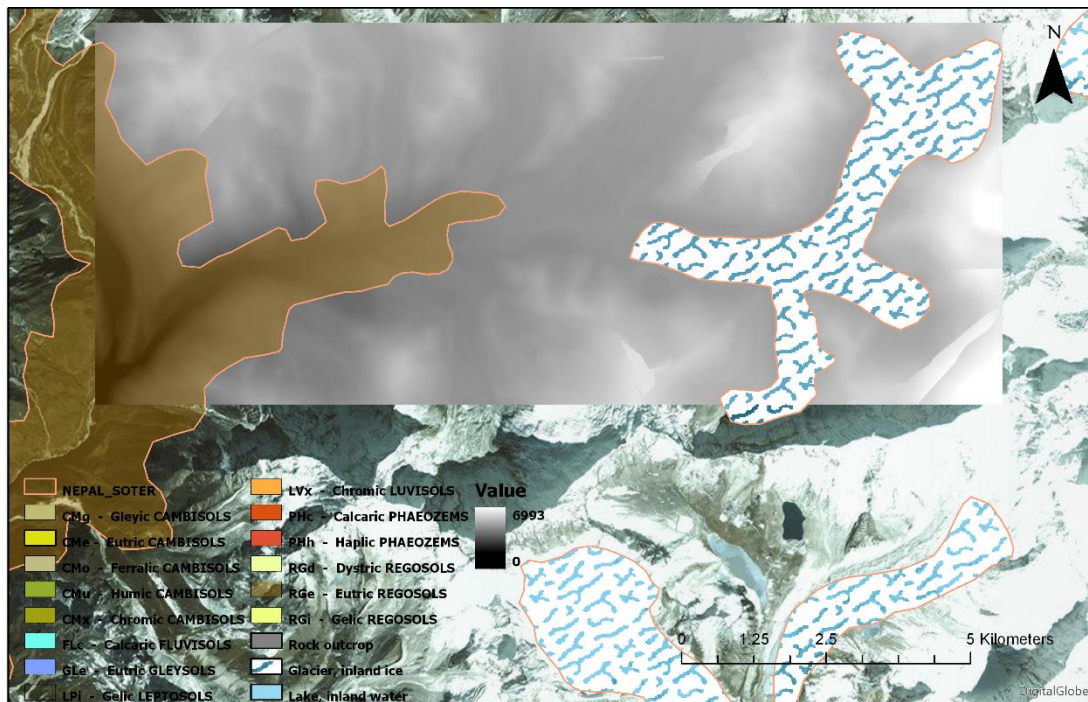


Figure 1: Combined DEM of Dingboche Valley with Soil Data

Note the gaps on the east side of the DEM that were filled using Focal Statistics. Since these exist on the mountain slopes, where avalanches may form, a second DEM was used. As before, holes were filled using Focal Statistics and Raster Calculator; however, the holes were located in areas less prone to avalanche, improving upon the initial DEM. Avalanche-prone areas were detected using the equation

$\tan \alpha = 1.11 - 0.118 \log(V)$, where α is the average trajectory slope and V is the volume of the avalanche (Rounce *et al.* 2016). This report considered a single large avalanche size of 6.7 million m³, with a starting depth of 50 m. Avalanche-prone areas are shown in red in Figure 2 below.

As the risk of a GLOF is much higher in the future, it was necessary to predict the lake extents for the next few decades. While the process used for this is outside the scope of this report (as this was completed well before the start of this class), the predictions generally used Monte Carlo simulations to generate random iterations of glacier retreat based on past retreat rates (Rounce *et al.* 2016). The results of these predictions are depicted in Figure 2.

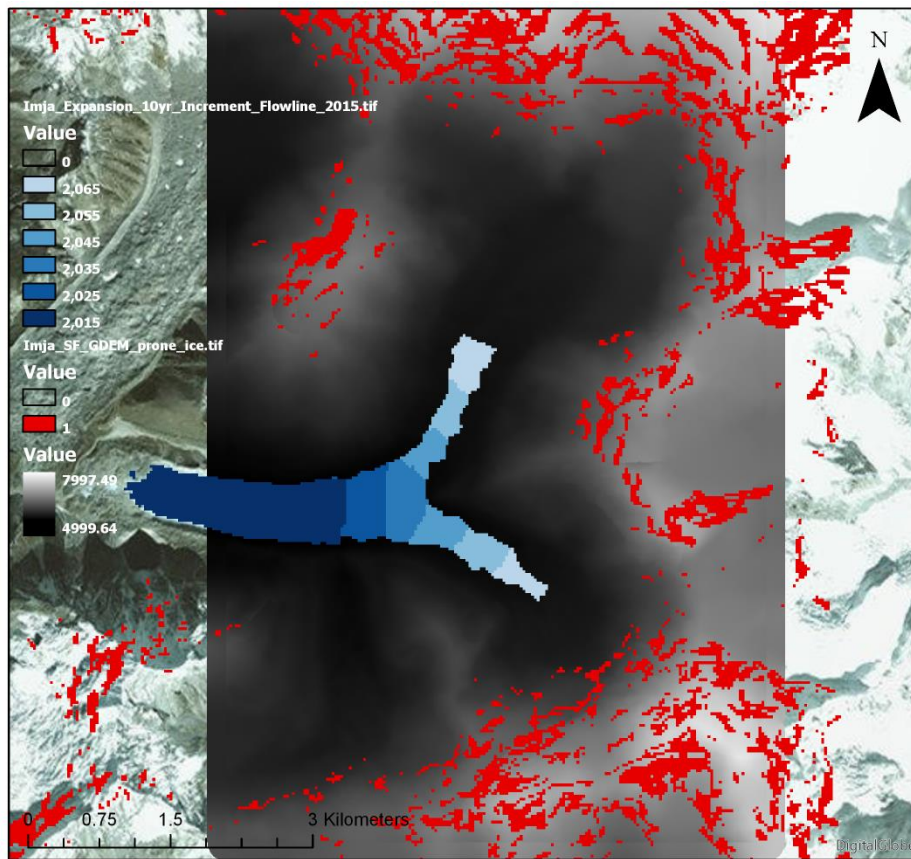


Figure 2: Input Geographic Data for RAMMS

Note the proximity of the avalanche-prone areas to the southernmost predicted extents of the lake. Additionally, the southern valley is straighter, meaning less energy is lost as an avalanche propagates downhill. For these reasons, the avalanche was chosen to originate directly southeast of the lake.

MODELING AN AVALANCHE WITH RAMMS

RAMMS software utilizes a DEM (Figure 2) and various debris parameters to model the path, flow height, velocity, pressure, and deposition of debris flow, including avalanches. The debris used in the model for this report has a density of 1000 kg/m³ (Somos-Valenzuela *et al.* 2016)—the same density as water—which allows the deposition into the lake to be interpreted as direct water inflow. The initial

block of debris was set at 50 m deep and with a volume of 6.7 million m³, which would be considered a large but reasonable scenario (Rounce *et al.* 2016). The results of the avalanche deposition are depicted below, in Figure 3.

The model produced ASCII files for deposition, which were converted into TIFF files using ArcGIS. To determine the hydrograph into the lake, values for each cell were recorded at each time step, and the values for all cells in a given time step within the lake extents for 2035 and 2045 were summed. This produced two hydrographs: one for deposition into the lake in 2035, and one for the lake in 2045 (Figure 4).

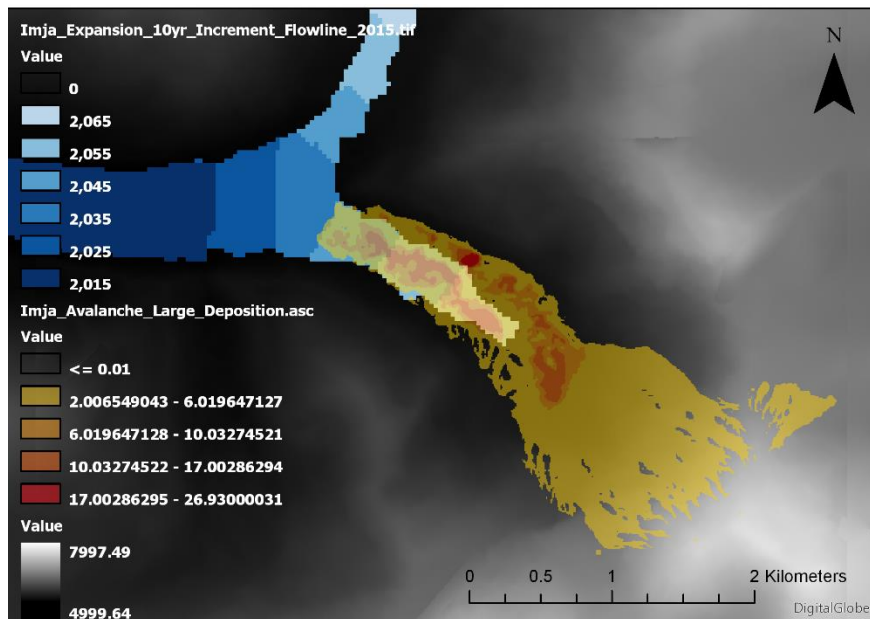


Figure 3: Avalanche Deposition

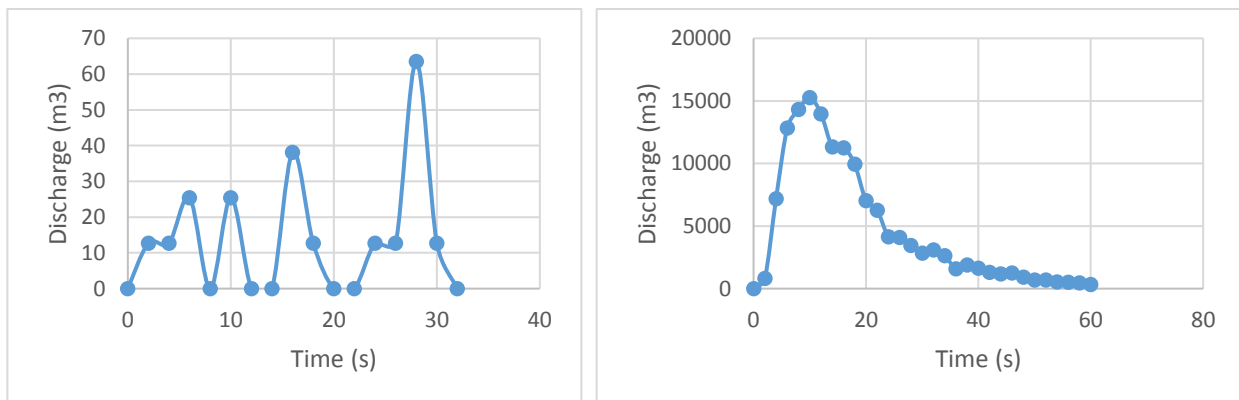


Figure 4: Inflow Hydrographs due to Deposition from Avalanche into Lake Extents at 2035 (Left) and 2045 (Right)

Note the small amount of deposition that reached the 2035 lake extents, which resulted in a variable hydrograph. In contrast, a larger amount of debris reached the 2045 lake extents, resulting in a smoother hydrograph. These outputs were written as text files and used as inputs for BASEMENT flood modeling.

FLOOD MODELING WITH BASEMENT

BASEMENT software utilizes triangular elevation meshes coupled with hydrologic and soil data to model environmental flows, including floods and related soil transport. Soil data was determined from field data along with the SOTER data for Nepal (see Figure 1), while hydrologic data was gathered from the inflow hydrographs previously generated (Figure 4) and an assumed lake elevation of 5007 m MSL. In order to make a usable terrain file, several preprocessing steps were carried out. Previous studies have concluded that lake depth is closely related to glacier ice thickness (Rounce *et al.* 2016). Bathymetry data for future parts of the lake was therefore assumed to be the thickness of the ice, for which a raster had already been created. Using the Raster Calculator geoprocessing tool, the bottom elevation of the glacier was stitched into the lake DEM for each cell within the 2035 or 2045 lake extents. While this yielded a useable DEM, there was still a discontinuity in elevations at the interface of current and future lake depths. To fix this, a polygon over the interface was rasterized (using the Polygon to Raster tool), set as NoData (using Set Null), and stitched into the DEM (using Mosaic to New Raster). Next, focal statistics interpolated values on either side of the interface, which was incorporated into the NoData cells to produce a newer, smoothed interface that could run with BASEMENT more efficiently (Figure 5).

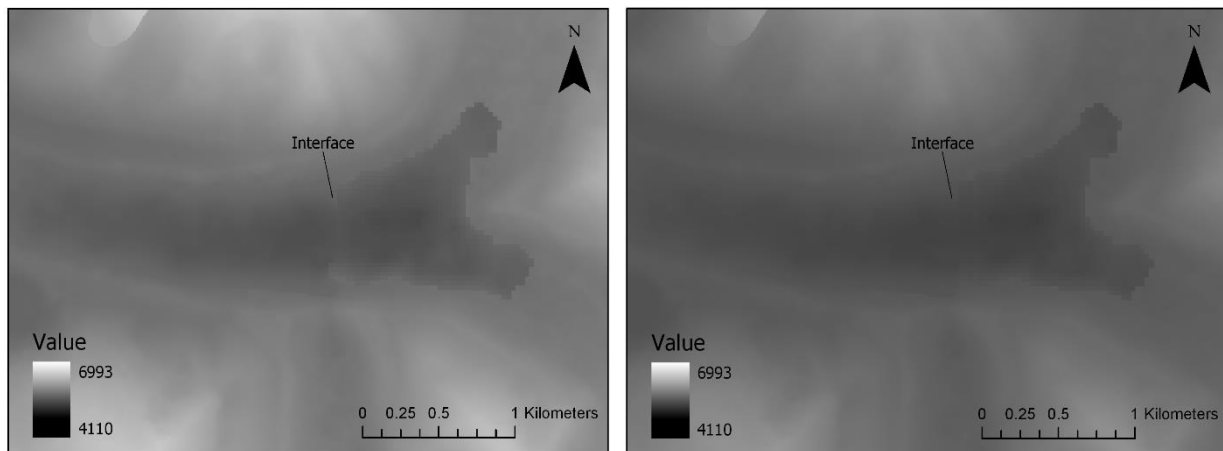


Figure 5: DEM of Lake in 2045 Before (Left) and After (Right) Smoothing

BASEMENT is designed to be used with QGIS, a free GIS software that allows for specialized plugins, including one produced by BASEMENT. This plugin produces triangular elevation meshes (known as Triangulated Irregular Networks, or TINs) which are read by the software in place of a traditional raster DEM. This process has several advantages; particularly, false sinks are less likely to be created, which results in a more accurate depiction of terrain for hydrologic analysis. For this project, QGIS created a TIN with a maximum triangle area of 1000 m² (Figure 6), comparable in resolution to a 30m DEM. While this is relatively coarse, meshes with smaller triangles lead to more errors in the model. Additionally,

this resolution is still fine enough to examine flooding around Dingboche, which is a relatively extensive village given its population.

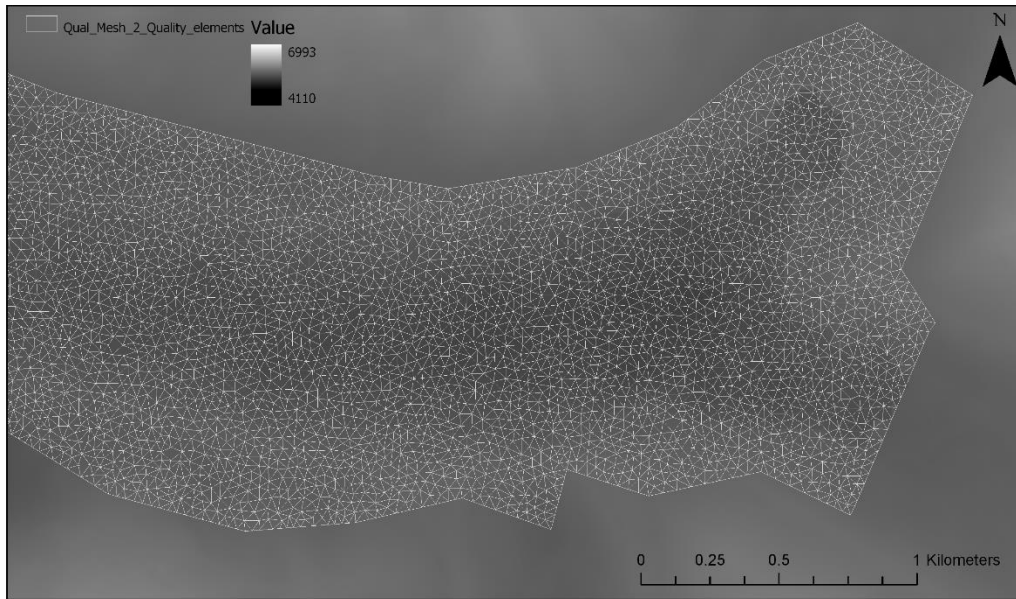


Figure 6: Triangular Mesh of Imja Lake

Using this mesh, in combination with the hydrologic and soil data above, two flood simulations were run: one for the lake in 2035 and one for the lake in 2045. In addition, a large hydrograph from a previous study was used to compare results.

RESULTS AND DISCUSSION

Both simulations did not result in a GLOF, so it was necessary to use the larger third hydrograph for the 2045 lake simulation. This produced a 17m-high wave (Figure 7) that overtopped the terminal moraine and caused a GLOF. Fortunately, however, this did not cause flooding at Dingboche, as the floodwater was confined to the river channel (Figure 8).

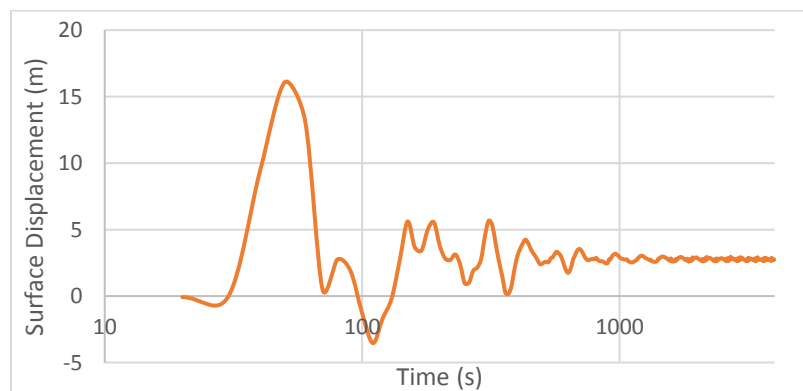


Figure 7: Wave Height at Center of Lake



Figure 8: Inundation Depth near Dingboche at t = 2000 s

Note how the surface displacement of the water in the lake increases from 0 to 2.7 meters—this is an indication that the terminal moraine did not fail, but simply overtopped; a failure would have resulted in a decreasing lake surface elevation. This is further indicated by analysis of the terminal moraine itself, in which discharge and elevation stabilize within a few minutes after overtopping (Figure 9).

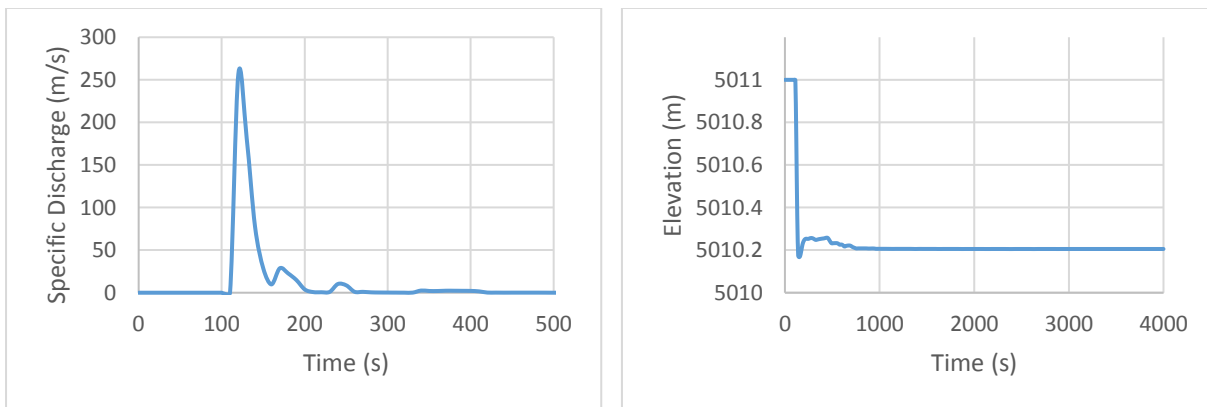


Figure 9: Specific Discharge and Surface Elevation at Element 5920 of Terminal Moraine

While these results are ultimately good news, they unfortunately provide no data for assessing damage based on different scenarios as originally planned, since no scenario resulted in a flood at Dingboche and only the most extreme scenario caused a GLOF at all. This data, however, conflicts with a previous study (Somos-Valenzuela *et al.* 2015), which provides an opportunity to assess the value of GLOF modeling via pure computational fluid dynamics (CFD) versus through dam breach models. In particular, the dam

breach model resulted in inundation depths of up to 21.8 m in the river channel, and up to 10 m in parts of Dingboche (Somos-Valenzuela *et al.* 2015). This is much higher than the results of this pure CFD BASEMENT model, which had a maximum depth of 3 m, all confined to the river channel. Again, this is likely due to the assumption of moraine failure, which did not occur in the BASEMENT model.

While the likelihood of dam breaching is a major concept to assess in the future, there are still other ways to compare the data of this model to the model developed by Somos-Valenzuela *et al.* (2015). In particular, the dam breach model predicts a peak discharge below Imja Tsho between 4272 m³/s and 19000 m³/s, with an expected value of 8394 m³/s, whereas the peak discharge using BASEMENT is only around 5500 m³/s. It should be noted, however, that the dam breach model assumed a lake surface elevation of 5010 m MSL, whereas new data indicates the lake is closer to 5007 m MSL—the value used in this BASEMENT model. Peak discharge, then, is smaller than expected but not by a large margin, as a lake elevation of 5007 m would have an expected discharge of 7131 m³/s according to the dam breach model (Somos-Valenzuela *et al.* 2015).

Since output discharges are similar between models, it is possible that moraine erosion/breaching differences are due to different assumptions of soil mechanics. While the BASEMENT model had some soil information from the SOTER database, the data was generalized and lacked resolution (i.e. there was no difference in soils between the riverbed and the surrounding land). Field data would be best to address this problem, and it is the intent of this research group to visit the lake in April or May of 2017. It may not be until this data is collected that a definitive model of a GLOF can be developed.

CONCLUSION

This project was useful in several respects. Firstly, it increased the author's knowledge and familiarity of GIS software and its applications, by requiring the synthesis of different kinds of data and geoprocessing techniques to achieve desired results. It also illustrated the connection between GIS and other aspects of water resources engineering, such as the numerical modeling software of RAMMS and BASEMENT. Finally, the project brought up a major challenge to previous GLOF studies of Imja Tsho, insisting that a GLOF is unlikely for the next few decades and that any triggering mechanisms will most likely not result in terminal moraine failure. While results on discharge from a GLOF are reasonable compared to previous studies, there are major differences in the behavior of the terminal moraine, ranging from minor erosion to complete breaching and failure. A lack of field data will be remedied with an assessment trip planned for April and May 2017, which will address any conflicting assumptions of soil mechanics between studies. It is the hope of this research team to have a full, comparative study of GLOF models by the end of 2017, which will further the team's goal of assisting the Nepali people and their government in making wise decisions to adapt to climate change.

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