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Term report: Glacial lake outburst flood (GLOF). Palcacocha Lake, Peru.

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1. Introduction

Palcacocha Lake in Peru is a tropical glacial lake subjected to Glacial Lake Outburst Flood (GLOF) risk. Knowledge about the behavior of an expected GLOF event in Palcacocha is required to identify emergency strategies to prevent human life losses and major infrastructure damage in downstream areas.

Due to climate change, retreating of glaciers is increasing rapidly. As a consequence, glacial lakes volume is growing as the ice melts and increases the deposited water volume. Among the hazards derived from the lake changes, floods have catastrophic effects on nearby areas life.

Such floods, commonly known as Glacial Lake Outburst Flood (GLOF), are caused by a failure in the natural dam (moraine) that holds lake water in place. The failure makes water contained into the lake be suddenly released. The formed wave represents high risk for downstream population located in the floodway.

By using Geographic Information Systems (GIS) and hydrodynamic modeling it is possible to asses the flood evolution in time and space. The flood travel time from the lake to the downstream towns and its magnitude (extent, depth and velocity) can be determined combining both tools. The present analysis focus on designing a GLOF model based on ArcGIS and Mike 11platforms applied to the Palcacocha Lake case.

2. Study area

This report is focused on the Palcacocha Lake region and its downstream areas, specially on Huaraz city, which is the main surrounding urban conglomerate.

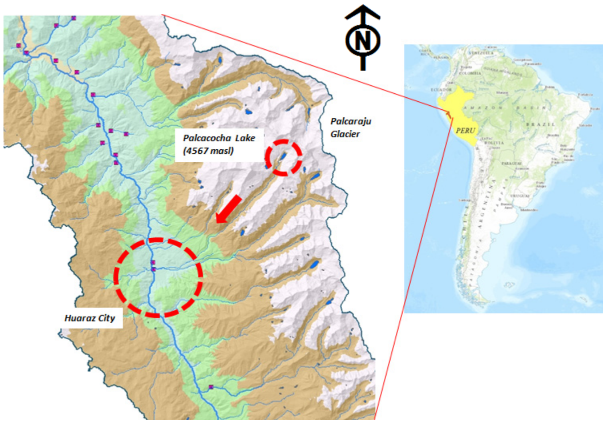


FIGURE 1. Location map. Palcacocha Lake. Ancash Region. Peru.

Palcacocha Lake is located at tropical latitudes in the Southern hemisphere at 9º23’50”S and 77º22’54”W, at an elevation of 4567m. It belongs to the Cordillera Blanca in Peru and it is fed by the Palcaraju glacier.

Despite the tropical environment in which the glacier is immersed, elevations in andean mountains are high enough to offer the climate conditions required by a glacier to arise and subsist. However, such conditions are becoming hostile due to climate change. Growing of Palcacocha Lake volume is an indicator of Palcaraju glacier melting and retreating.

Palcacocha Lake changes have been documented since 1972, indicating its volume is growing rapidly. In 1972 the volume was approximately 0.5 millions m^3, while the last bathymetry measures indicated that by 2009 it has exceeded 17 millions m^3.

TABLE 1. Palcacocha Lake. Historical growing.

Year	*Area (m^2)*	*Volume (m^3)*	*Max. Depth (m)*
1972	66,800	579,400	14
1974	62,800	514,800	13
2003	342,332	3,959,776	15
2009	518,426	17,325,207	73

The main risk concern about a GLOF event in Palcacocha is that Huaraz city is located 23km downstream from the lake. Cojup creek, whose origin is Palcacocha, drains into Quilcay River, which flows directly through Huaraz city before joining Santa River.

Historical catastrophic events precede current concerns about a new GLOF event in Palcacocha. In 1941 the end moraine failed, causing a flood that destroyed part of what was a small Huaraz city. According to Carey (2010), 5000 people died because 1941 flood.

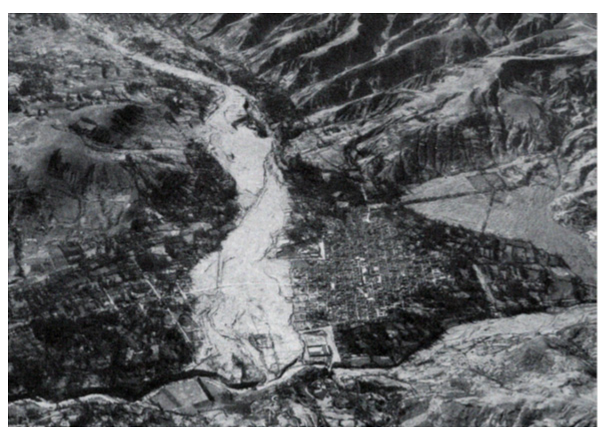


FIGURE 2. Huaraz city covered by the 1941 flood.

In 1941 the lake volume was less than 12 million m^3. By 2010 it had already exceeded 17 million m3. Otherwise, the critic volume has been estimated to be 0.5 million m^3 (National Institute of Civil Defense, 2011).

Huaraz city has grown since 1941. It is now the capital of the Ancash region and its main touristic center. Its population has been estimated as 120,000 inhabitants (INEI, 2007). As the population and water volume has increased, the GLOF hazard has become higher than it was in 1941.

3. GLOF modelling

3.1. Conceptual model

The adopted approach to reproduce a GLOF event in Palcacocha Lake is based on the creation of a terrain representation, over which hydraulic calculations are performed by a hydrodynamic model. The results are produced and presented by the interaction between both models. It is a preprocessing - processing and postprocessing approach.

The geometry inputs of the hydrodynamic model are extracted from the terrain and the processed results are overlapped on the same terrain in order to obtain a spatial and temporal representation of the flood flow over a map.

3.2. Terrain model

The modeling results can be just as accurate as the input data. The best available terrain information from Palcacocha-Huaraz area is a 30m resolution ASTER[1] Digital Elevation Model (DEM). Although partial LIDAR[2] data was obtained, it covers just a fraction of the Cojup Creek length to be modeled.

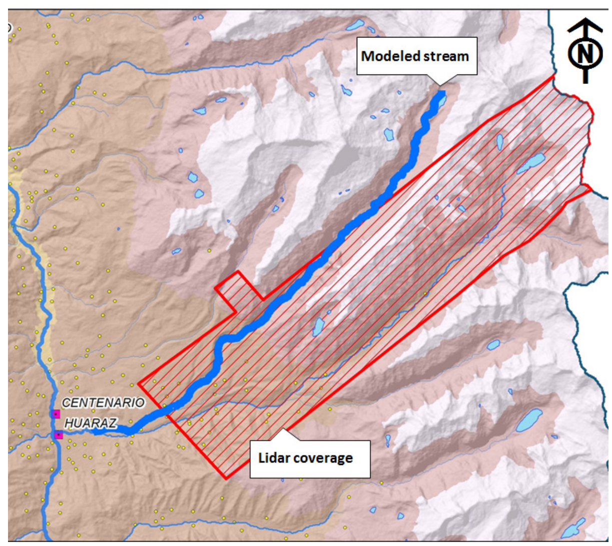


FIGURE 3. Coverage of available Lidar data

The magnitude of the event (flow depths of 10m order are expected for peak discharges) reduces the impact of low terrain accuracy on calculations over

1. Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) is a space mission launched by Japan and United States agencies. Since 2011 the second version of the produced 30m DEM was released for public distribution.
2. Light Detection And Ranging (LIDAR) is an optical remote sensing technology. The gathered raw data did not contain the required statistical measurements (average point distance) to process it. Such measurements were estimated by using GIS tools.

canyon shape intervals of the stream. However, on flat areas, the effect of terrain inaccuracy is unavoidable.

To estimate the order of magnitude of the 30m DEM error in relation to high accuracy measurements, a new Digital terrain Model (DTM) has been built using the LIDAR raw data.

The mean square deviation between them is $135.32m^2$, which suggests the error of the elevation values of the 30m DEM is approximately $\pm 11.6m$, which is high in relation to the expected depths (around 10m), but less than the official reported average accuracy of global ASTER DEM (15m). Thus, the 30m DEM has been used as the terrain model, taking into account the final results will be highly susceptible to depth errors.

One dimensional hydrodynamic models require to transform raster represented DEM's into discrete transects distributed along the stream axis. The transects and the stream axis has been extracted from the DEM using a preprocessing plug-in for ArcMap called MIKE-GIS[1].

The distance between transects is set based on the accuracy of the data, but also it is intended to be short enough to provide a smooth transition between cross sections. Such transition makes easy to find a stable numerical solution for the upcoming hydrodynamic model. A constant interval between sections of 90m has been used to extract the cross sections.

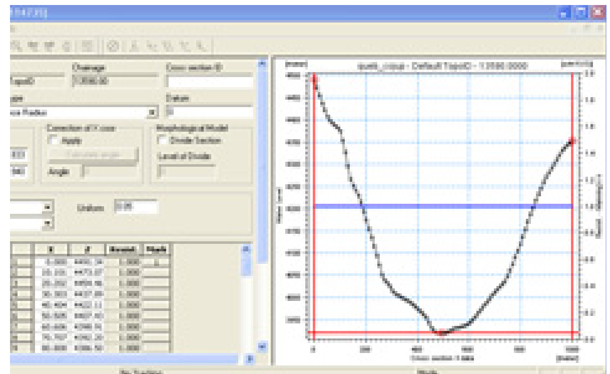


FIGURE 4. Capture of the transect extraction interface

The final discrete terrain model is composed by a 24.6 km stream and 201 cross sections, which represents Cojup Creek, from Palcacocha Lake to Huaraz city limits.

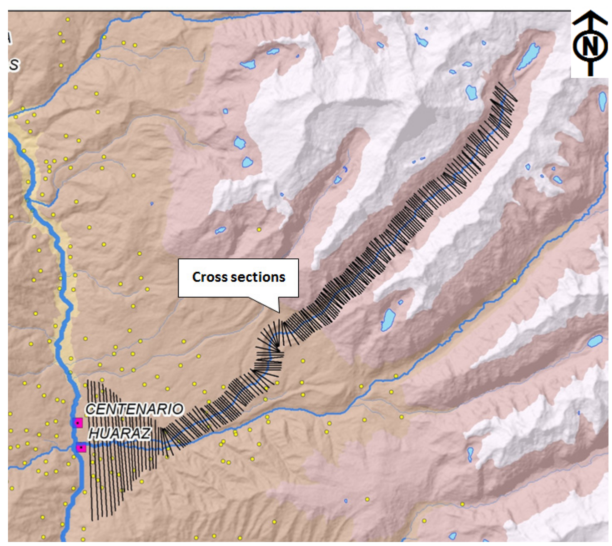


FIGURE 5. Cross sections extracted from the 30m ATER DEM.

1. MIKE-GIS is the geospatial component of the MIKE 11 by DHI package used for hydrodynamic modelling.

3.3. Hydrodynamic modeling

The hydrodynamic calculations were performed using MIKE 11, a one dimension unsteady state model. Three components are required to define a GLOF process using such platform: lake volume, breach formation and the hydrodynamic parameters of the streamflow.

Lake volume. A bathymetric curve represents how the lake volume changes as a function of elevation.

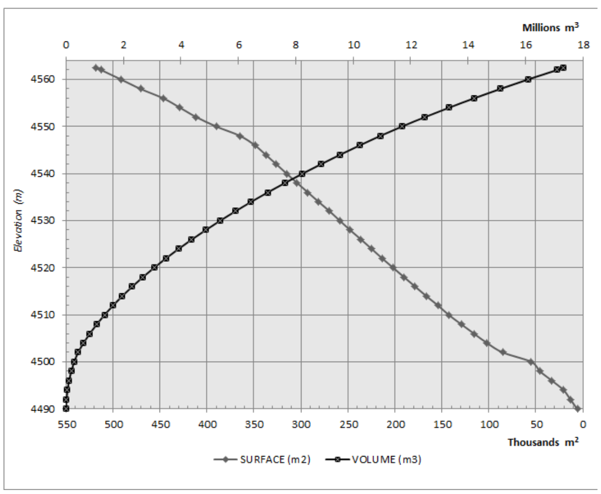


FIGURE 6. Palcacocha Lake elevation - volume curve

Thus, it is related to the rate at which water will be released as the dam breach grows. A curve extracted from a bathymetry surface of Palcacocha Lake (National Institute of Civil defense, 2009) is shown in Figure 6.

Breach formation. There is no much information about the moraine internal structure. It is known it is composed by debris, rock and ice deposits, but it is uncertain how a breach would form and behave on it. It will be assumed an overtopping failure, as suggested by Popov (1991), who proposed an empirical relation to estimate the expected maximum flow for the GLOF as a function of the lake volume. The characteristics of the breach, including the time of formation, can then be adjusted to approximate the peak of the modeled GLOF hydrograph (dam break model) to the Popov's equation maximum flow $Q_{max} = 0.0048 V^{0.896}$, where Q_{max} = maximum flow (m^3/s) and V = volume of the lake (m^3).

Using the bathymetry data, the maximum discharge is $14,445 m^3/s$. The required formation time of the breach shape shown in Figure 7, under the established constraints, is approximately *30min*.

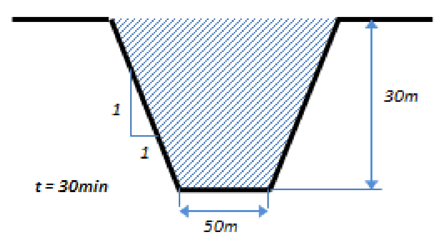


FIGURE 7. Breach geometric characteristics

Hydrodynamic parameters. To gain numerical stability, the simulation time step has been set as 1 second and constant base flow of $200 m^3/s$ has been introduced as initial condition. A simulation period of 4 hours covers the entire GLOF process, since the breach failure until the lake volume has been completely drained.

The selected resistance flow expression is Manning's equation. The applied n coefficient is 0.005 as recommended by Chow (1959) for mountain rivers.

4. Results

Under the adopted dam breach formation hypothesis the arrival time of the flood to Huaraz urban area is 22 minutes, while the peak downstream discharge (maximum flow) is produced 33 minutes after the breach failure starts.

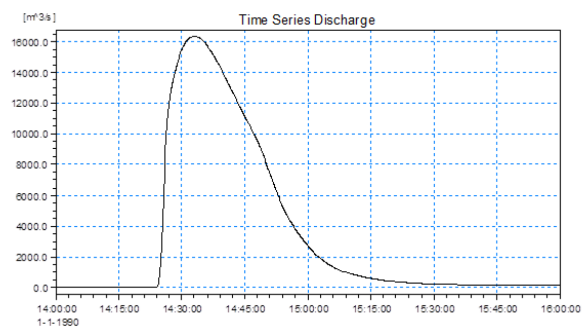
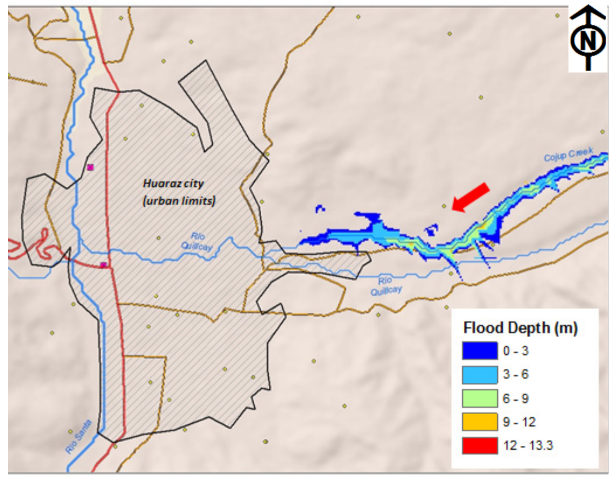


FIGURE 8. Huaraz city limits GLOF histogram

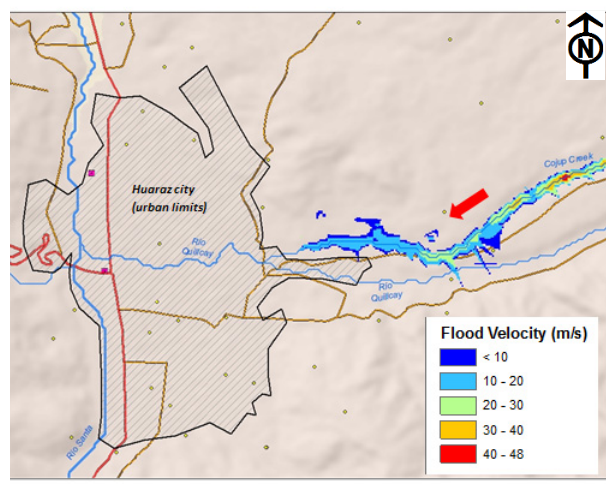
The water residence time, until the water is completely drained from the stream, is 70 minutes.

Spatial and temporal distribution of GLOF depth and velocity are represented as time series surfaces (rasters). Figure 9 shows water depth and velocity at flood arrival time to Huaraz city limits.

The full time series raster is compressed by a multiband file (dfs2 format), in which each band contains the results for each simulation time step.



(a)



(b)

FIGURE 9. GLOF stages at Huaraz city limits: (a) flood depth at arrival time, and (b) flood velocity at arrival time.

Specific affected rural neighbors, located in the floodway, are summarized in Figure 10 and Table .

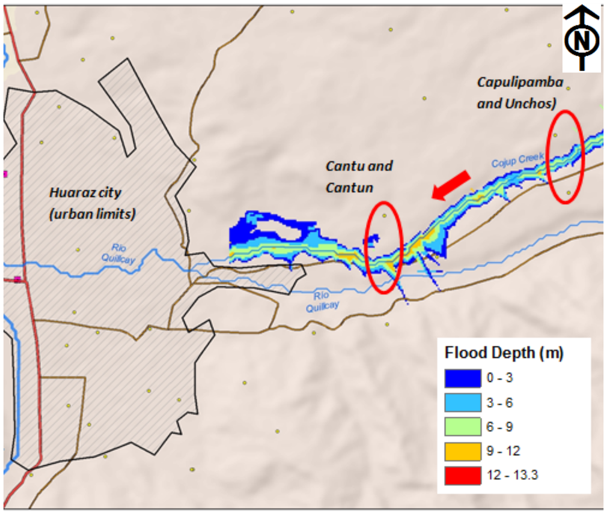


FIGURE 10. Maximum flood depth envelope and affected rural towns

The lag time since the peak discharge leaves the moraine and arrives to the downstream areas is 18 min. Therefore, the average GLOF wave celerity is $82 km / h$.

TABLE 2. Flood arrival time and maximum velocities in Huaraz inhabited areas

Towns	*Arrival time (min)*	*Max. Velocity (m/s)*
Capulipamba and Unchos	19	48.5
Cantu and Cantun	20	25
Huaraz Urban Area	22	20

The catastrophic damage of the 1941 GLOF is explained by the estimated velocities. A 20 m/s (45 mph) wave has enough power to knocks a person down even if it only comes up to the knees. A flood of this nature gathers debris (trees, mud, rocks, etc.) and they create more destruction as they crash into other objects.

As long as flat terrain is not reached, the model produces stable results. When floodplain is approached, before the junction of Cojup Creek and Quilcay River, results are not longer reliable. Therefore, model results are presented just for sections where they can be considered representative of the actual flood.

The plain area of Huaraz could not be modeled. However, the 1941 antecedent and the partial results show the susceptibility of Huaraz city to a GLOF event.

5. Conclusions

Although the applied approximations and inaccuracies around the proposed model affects the reliability of the results, the order of magnitude of depth, velocity and time is enough to asses the hazard into which downstream communities are immersed.

According to the results, there is no enough available time (around 20 minutes) to perform an emergency evacuation plan once the GLOF has started.

Emergency structures (downstream engineered dams) or reduction of the lake water volume are measurements might be considered as solutions to reduce the GLOF hazard in Palcacocha Lake. Feasibility studies for each alternative should be supported by models similar to the presented in this report.

To predict the impact of a GLOF in the urban core of Huaraz city, a two dimensions model is recommended to extent results to flat areas. Moreover, the current model exclusively reproduces water flow, while the expected fluid is mostly a mixture of mud, sediment and water (debris flow).

6. References

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LOCATION MAP

Palcacocha Lake. Ancash Region. Peru

0 2 4 8 km

Projection: Universal Transverse Mercator. Zone 16S
Datum WGS84

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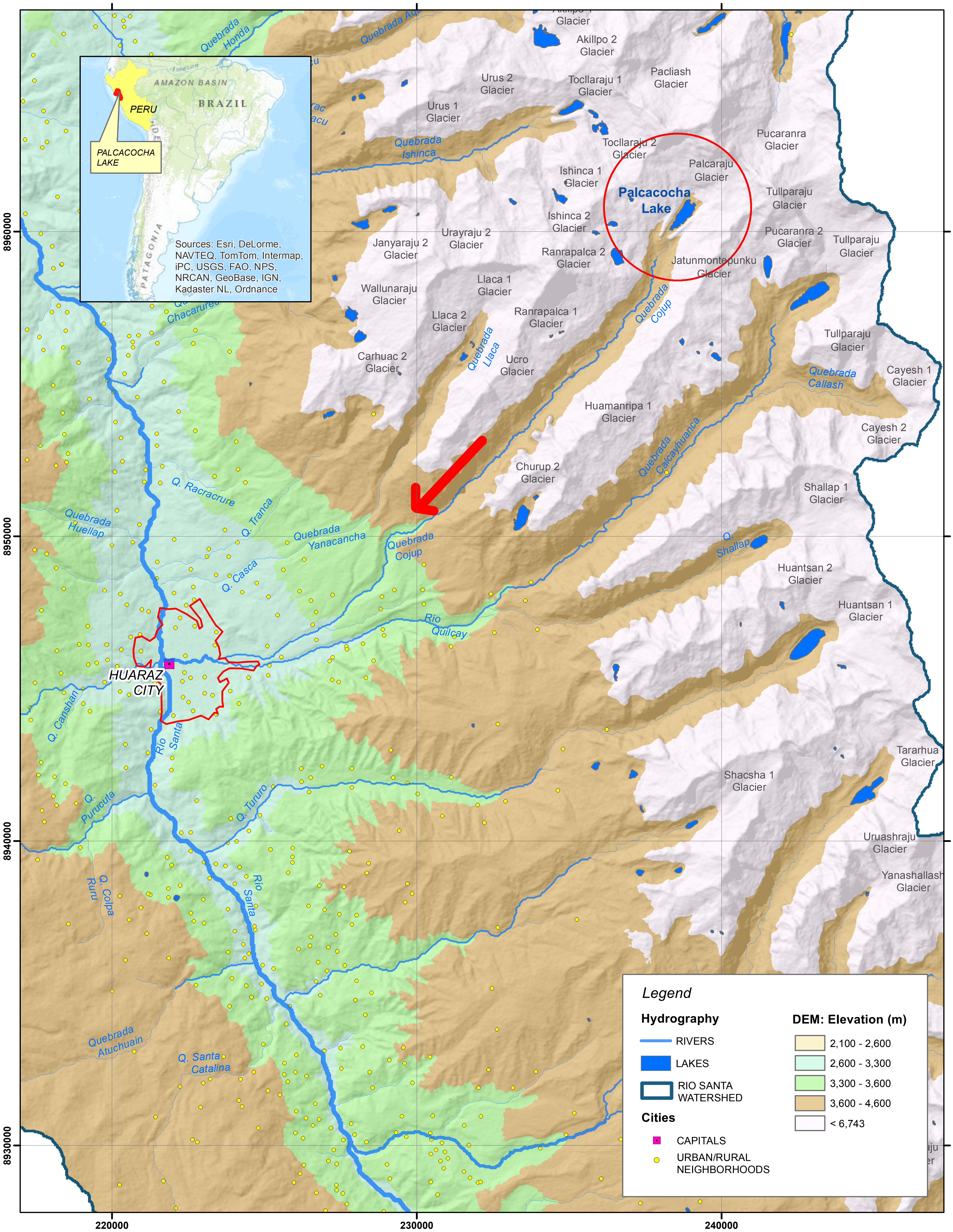

TERRAIN DEFINITION

Palcacocha Lake. Ancash Region. Peru

0 2 4 8 km

Projection: Universal Transverse Mercator. Zone 16S
Datum WGS84

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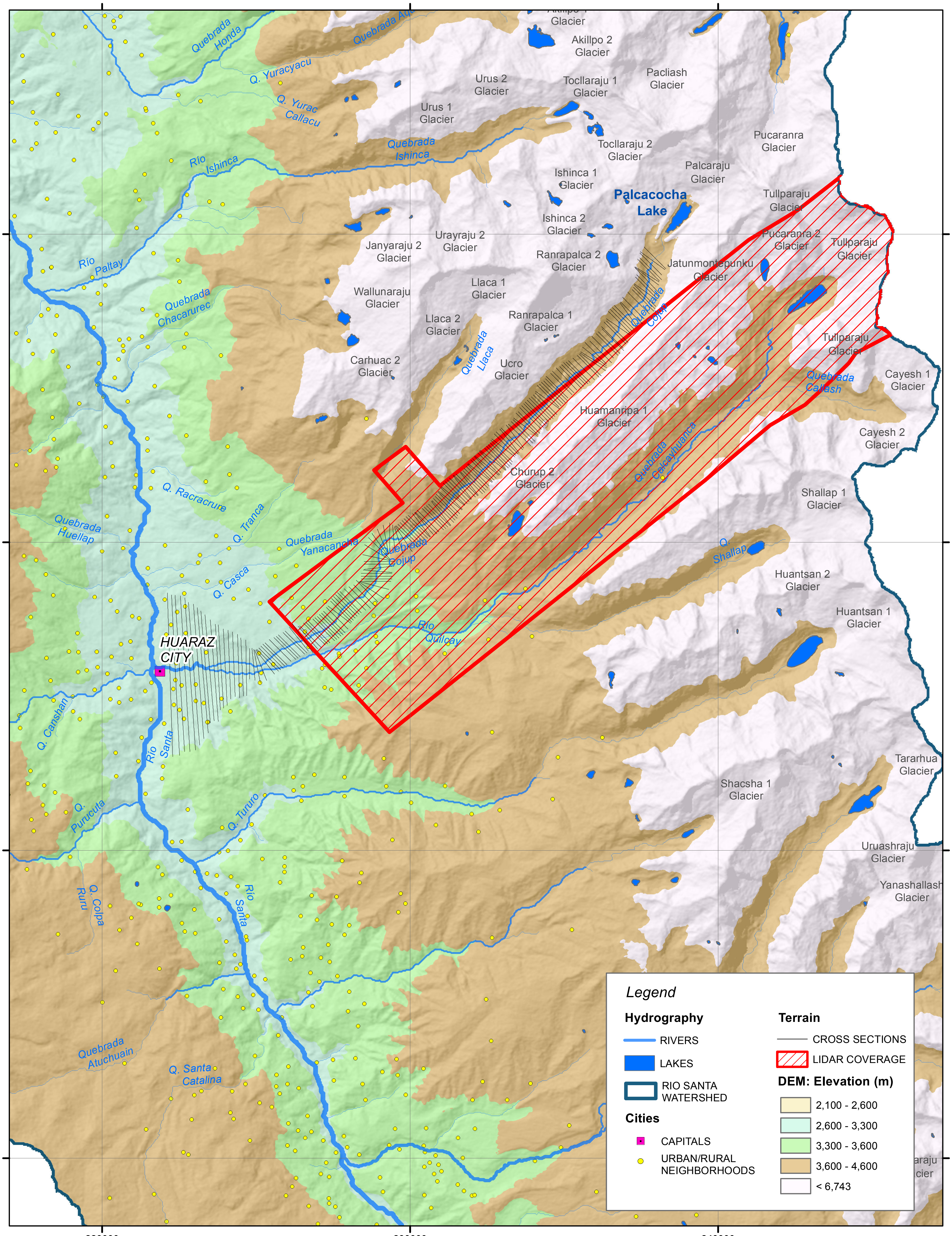

GLOF MAXIMUM DEPTH

Palcacocha Lake. Ancash Region. Peru

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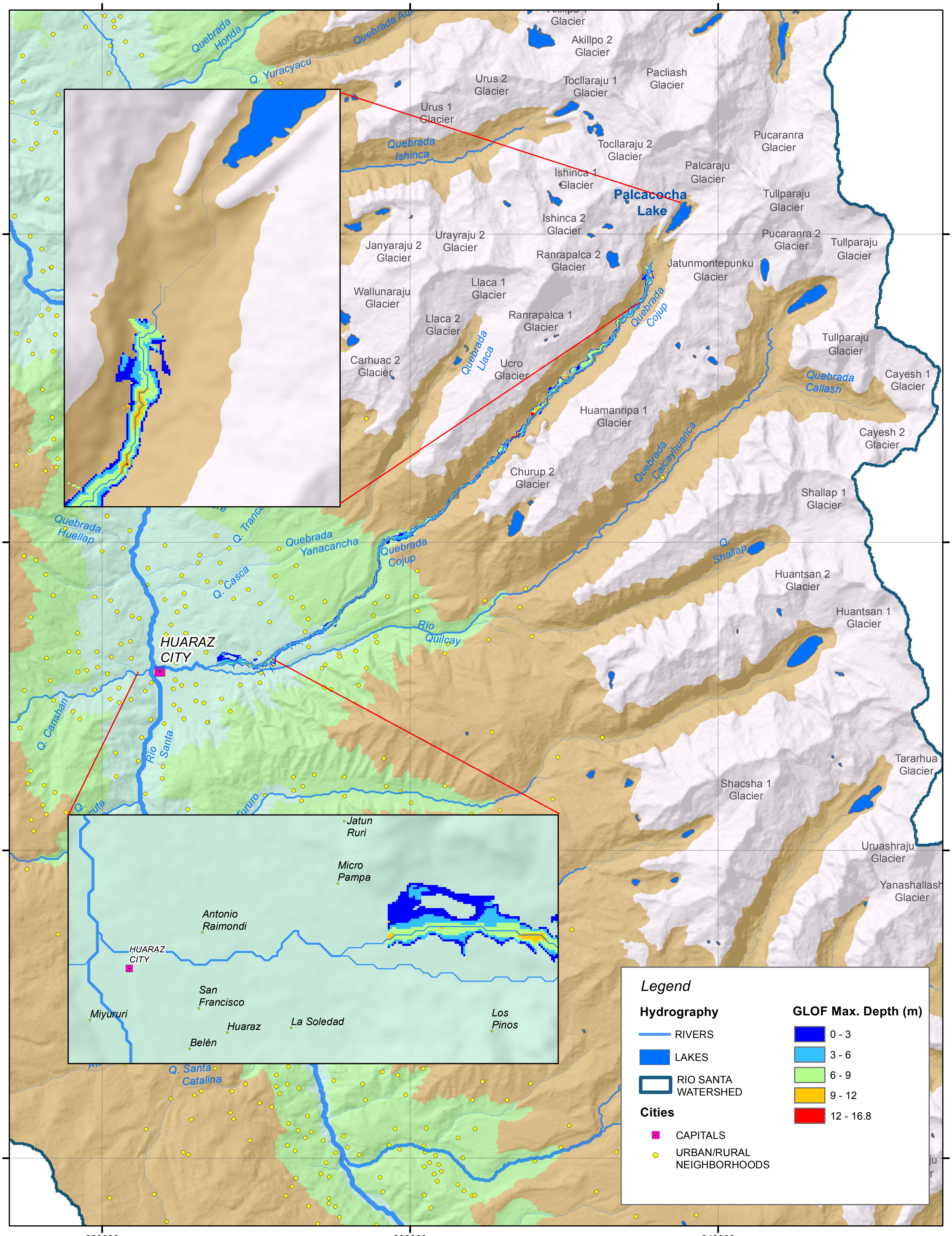
Projection: Universal Transverse Mercator. Zone 16S
Datum WGS84

N



GLOF MAXIMUM VELOCITY

Palcacocha Lake. Ancash Region. Peru

0 2 4 8 km

Projection: Universal Transverse Mercator. Zone 16S
Datum WGS84

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