# Connecting Tibetan lake level and glacial thickness changes

## A study on the Tibetan plateau using ICESat height measurements

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## Abstract

Climate change is changing our world. Glacial boundaries are retreating and weather patterns are changing. The Tibetan plateau contains thousands of glaciers and lakes. The plateau is the origin of many major rivers including: Ganges, Indus, Yangtze and Yellow river. The rivers support a large ecosystem and millions of people.
To find out how climate change affects these glaciers and rivers, research has been carried out about lake and glacial level changes in Tibet with ICESat laser altimetry data from 2003 to 2009 by Ir. V.H. Phan in recent years (his PhD thesis is almost finished). A relatively small number of Tibets glaciers (122) and lakes (154) had been sufficiently sampled from 2003 to 2009; the period in which the ICESat satellite was operational.

In this bachelor thesis the connection between the glaciers and lakes sampled by ICESat are researched, especially the correlation between lake and glacial vertical changes. QGIS will be used for analysing and presenting the data.

The available data consisted of SRTM altitude data and derived data on river systems and watersheds. Using QGIS an analysis was done to determine which glaciers and lakes were in the same watershed. When there were sampled glaciers and lakes in the same watershed and the lakes were dependent on glaciers, a visual inspection was made to confirm that a sampled lake received glacial runoff from a specific sampled glacier.

In total 19 connections between glaciers and lakes from V.H. Phan's studies were found. This is quite a large number of connections. Especially considering the fact that in the great river basins, glacial runoff is often transported out of Tibet through the river systems and no lakes are visited on the way.

From the analyzed data the following conclusions can be drawn:

- It is clear that most lake levels are rising in Tibet and that the relative area of glaciers for a watershed (RU value) does not seem to have a big influence on lake level change. The rate of lake level change is different for different regions.
- There is no clear trend in glacial thickness change as function of altitude for the complete area of Tibet, but there is a clear trend for different basins. The difference between different basins can be very large.

To check the results, three case studies were made, which confirmed that glacial runoff has only a very small impact on lake level change. So no clear direct correlation between change in glacial thickness and lake level change can be made. The change in temperature and weather systems has probably a much larger impact.

It looks like that there is an indirect correlation between the change in glacial thickness and lake level change: they both follow the increase or decrease of precipitation. This should be studied further.

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## 1. Introduction

Because of active orogenesis (mountain forming) the Tibetan plateau is exceptionally high, 5,000 m on average (Andrew Alden, Geology, About.com). The Tibetan plateau and surroundings contain the largest number of glaciers outside the polar regions (Yao et al, 2012). There are 34,000 glaciers in Tibet with a combined area of over 50,000 $km^2$ (V.H. Phan et al, 2013). These glaciers form the origin of many major rivers including: Ganges, Indus, Yangtze and Yellow river. The rivers support a large ecosystem and 1.5 billion people in Asia (C. Levacher, 2014). The decrease or increase of water flow through these rivers will have a major impact on those who are dependent on it.

Because of climate change the atmospheric circulation pattern and the average temperature is changing. An average temperature rise of 1.8°C has been recorded since 2006 for the Tibetan plateau (B Wang et al, 2008).
The present atmospheric circulation patterns over the Tibetan plateau and surroundings are characterized by the Indian monsoon in the summer and the Westerlies in the winter. These two circulation systems, combined with the huge topographic landform, exert climate controls on the distribution of existing glaciers (Yao et al, 2012).
In figure 1.1 the monsoons are shown in combination with the Equilibrium Line Altitude (ELA). The equilibrium line marks the boundary between the accumulation and the ablation (decreasing) area of a glacier. The ELA's are high in places with low precipitation and lower in areas with high precipitation. The ELA's are given in meters above sea level.
Changes in weather patterns have caused precipitation increases in the Western part of the Tibetan plateau, because the Westerlies are getting stronger. The Indian monsoon coming from the South to the interior is weakening and as a result the precipitation has decreased. In the East, the East Asian monsoon is providing precipitation but this monsoon is not as strong as the Westerlies. The interior of the Tibetan plateau is less influenced by the monsoons and is dominated by continental climate conditions (Yao et al. 2012). In a sense the mountain rigs preserve a continental climate and keep the monsoons (Westerlies and Indian monsoon) out.

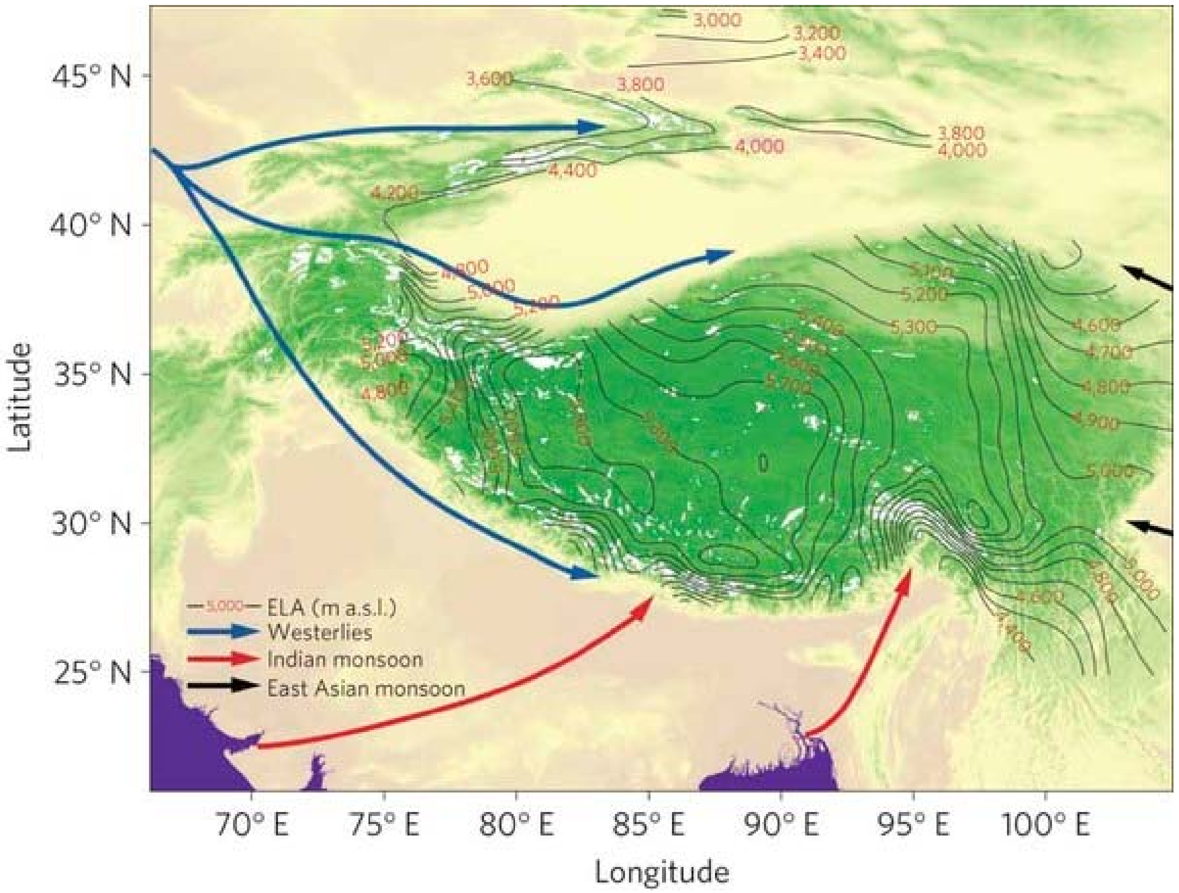

**Figure 1.1: Westerlies, Indian and East Asian monsoons with ELA's for Tibet (Yao et al. 2012)**

Because of these climate changes the glaciers are changing. Most glaciers are decreasing in length and the equilibrium lines of the glaciers are retreating up the mountains. These changes are very visible on location and from satellite pictures over a period of time. But a glacier is also changing in thickness and this is less easily visible (especially for satellite photos). The Geoscience Laser Altimeter System (GLAS) onboard the ICESat satellite has made laser height measurements between 2003 and 2009. The data this satellite has gathered is used to analyse surface level changes for glaciers and lakes in Tibet (and the rest of the world).

At Delft University of Technology, research has been done by Ir. V.H. Phan with ICESat laser altimetry data to find vertical changes in lake levels and in glacier thickness in Tibet. In this bachelor thesis the glaciers and lakes selected by Ir. V.H. Phan will be researched.

First of all, in chapter 2, the different data sources used will be described. Two types of data sources are used: height changes measured by ICESat, and processed data about the dependency on glacial runoff for a lake's water supply.

From these data sources it can be determined which lakes and glaciers are connected. There is a connection if melting water from the glacier flows into the (connected) lake. When a connection is found, correlation between lake and glacial vertical change will be looked at. The used methods are presented in chapter 3. The results will be described in chapter 4, including an analysis of the changes of glacial thickness and lake level changes.
The results are further researched in some case studies, so a selection of 3 lakes and their supplying glacier(s) is discussed in chapter 5. Chapter 6 deals with the results found and a global discussion. In chapters 7 and 8 conclusions and recommendations are presented.

## 2. Data sources

For this research, different data sources have been used. They are divided in primary data sources and derived data product. Primary data is data on topography, hydrological data and layers containing lakes and glaciers, and is freely available on the internet for every place on Earth. The derived data products are data files containing height changes for lakes and glaciers and the dependency of glacial runoff for lakes are available for the area of Tibet. These are made from freely available data.

### 2.1. Primary data

Primary data is called primary because when downloaded they are directly usable without alterations. The data is accessible to anyone on the internet for free. This data covers the entire Earth or at least the largest part. This data is often available for smaller areas because otherwise the file would require too much computer power when used. The files used will be described below in more detail.

#### 2.1.1. SRTM elevation data

The Shuttle Radar Topography Mission (SRTM) was a mission carried out by the space shuttle Endeavour. Over a period of 11 days in February 2000 a modified radar system generated the most complete high resolution digital topographic database of the earth. The data is recorded in decimal degrees and datum WGS84.

WGS84 is the World Geodetic System 1984, a widely used coordinate system which uses a standard coordinate system (latitude & longitude), a standard spheroidal reference surface and gravitational equipotential surface: the geoid. The geoid defines the nominal sea level (and is used for defining altitude). The geoid data is available in blocks of 5x5degrees. The altitude accuracy is 5m on flat terrain and 16 m on steep and rough terrain (Zandenberg, 2008).

A part of the SRTM layer is shown in figure 2.1.A below.

This elevation data is freely available from the CGIAR Consortium for Spatial Information (CGIAR-CSI) website in ARC GRID, ARC ASCII and Geotiff format:

http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp

#### 2.1.2. HydroSHEDS

HydroSHEDS stands for Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales. The basis for HydroSHEDS was the SRTM data at 3 arc-second resolution, which was used to approximate the river systems and watershed boundaries. An arc-second is Pi/648,000 and therefore dependent on latitude (circle around Earth is smaller away from equator). Three arc-seconds equals to about 87m in Tibet and a resolution of three arc-seconds is built out of grid cells with sides of about 87m.

The approximation was made by the U.S. Geological Survey by hydrologically conditioning the SRTM data using automated procedures. Algorithms were used for void-filling and stream burning (for more information visit the U.S.G.S website mentioned below).

In this research, only the river network and watershed boundaries were used. The watershed boundaries mark the different drainage basins (water divides). A part of the rivers and watersheds are shown in figure 2.1.B.

The used river network and watershed boundaries for Asia have been downloaded from the U.S. Geological Survey (USGS) website: http://hydrosheds.cr.usgs.gov

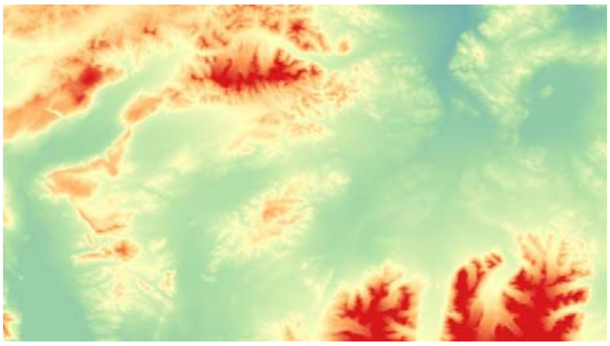

**Figure 2.1 A: SRTM layer**

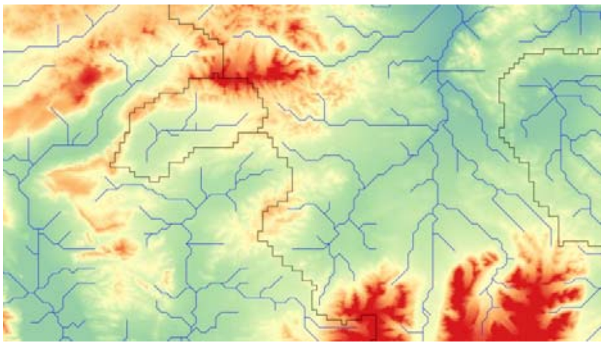

**Figure 2.1 B: HydroSHEDS layers**

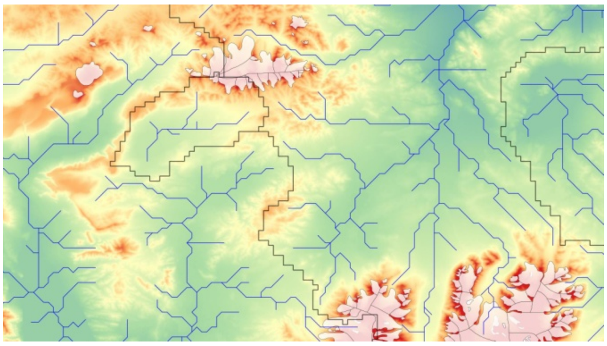

**Figure 2.1 C: GLIMS glacier mask**

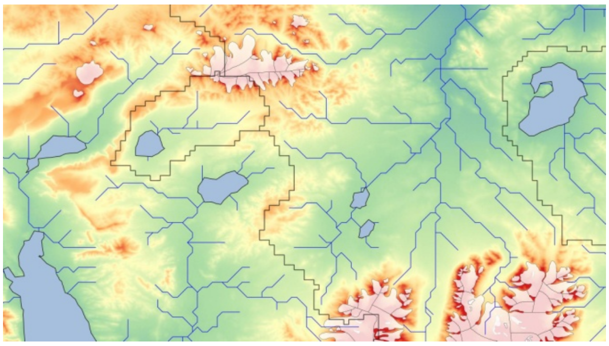

**Figure 2.1 D: MODIS MOD44W land water mask**

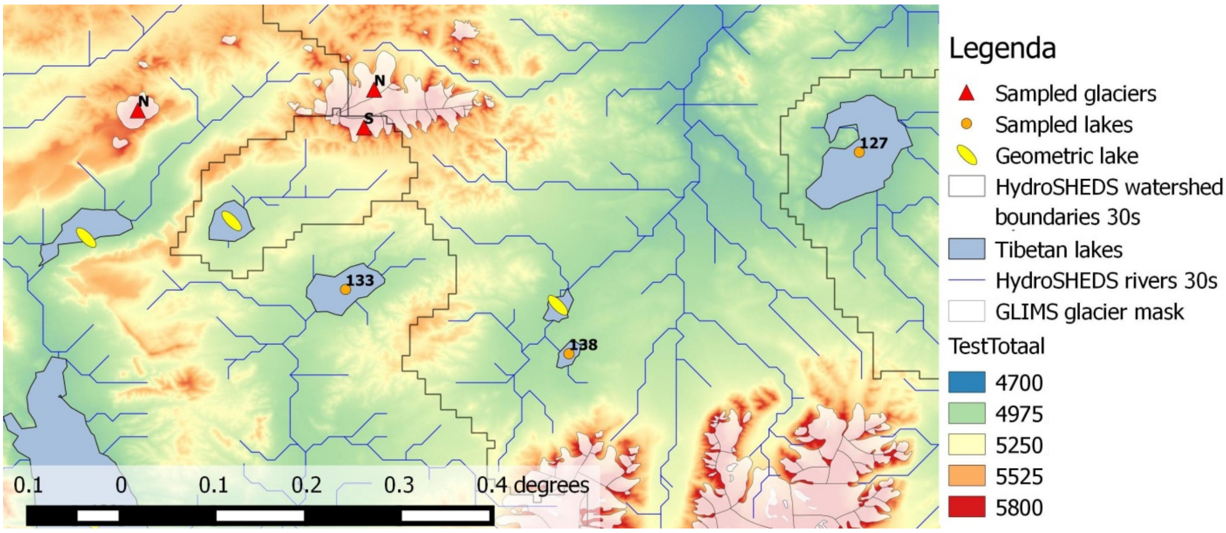

**Figure 2.1 E: The location of sampled glaciers and lakes (lake Nr. 133, location 33.7381°N, 90.6389°E).**

## 2.1.3. GLIMS/ CAREERI glacier mask

The Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science (CAREERI), created a map containing the world's glaciers. The glacier inventory was based on topographic maps, aerial photography, optical remote sensing images and in situ measurements from 1978-2002 (Shi et al, 2009). The GLIMS glacier mask is a copy of the CAREERI glacier mask but its format is changed to the WGS84 format (old format: Beijing Coordinate Projection). Every glacier is given by a polygonal vector. The attribute file gives an identification code for every glacier and the name, area, length, width, and minimal, maximal and mean elevation for that glacier. A part of the GLIMS glacier mask is shown in figure 2.1.C.

The GLIMS glacier mask was downloaded from GLIMS Glacier Database from the National Snow and Ice Data Center (US): http://glims.colorado.edu/glacierdata

### 2.1.4. MODIS MOD44W land water mask

The MODIS 250 m Water-land mask named MOD44W is a mask that contains two layers: Water and land. MODIS (or Moderate Resolution Imaging Spectroradiometer) is an instrument on two satellites to acquire data in 36 spectral groups of wavelengths. Every pixel is a square with sides of 250m. The mask is made using three data sources:

1. SRTM Water Body Dataset (SWBD) for areas between 60° S to 60° N.
2. The MOD44C, a non-public, 250 m global 16-day composite collection based on over 8 years of Terra MODIS data, and over 6 years of Aqua MODIS data (This data set originally provided the input to produce the Vegetative Cover Conversion, and Vegetative Continuous Fields products). Used for areas between 60° N to 90° N.
3. MODIS-based Mosaic of Antarctica (MOA), a 250 m MODIS area of Antarctica for areas between 60° S and 90° S.

The land-water mask used is a version of MOD44W, adapted by Ir. V.H. Phan for the area of the Tibetan plateau. A part of the modified MODIS MOD44W land water mask is shown in figure 2.1.D The original MODIS MOD44W was downloaded from the National Center for Ecological Analysis and Synthesis (NCEAS) website: https://projects.nceas.ucsb.edu/nceas/projects/environment-and-orga/repository/revisions/4ef959c29c64c93960a91f7bf27f9b6845e8c5c3/entry/climate/procedures/MOD44W.R

## 2.2. Derived data products

The derived data products are data on glacial changes which were derived from a larger data set by Ir. V.H. Phan. The data available on internet is not directly usable. Also information about the dependency of lakes on glacial runoff was derived from available data on the internet by Ir. V.H. Phan.

### 2.2.1. ICESat elevation data (GLA14).

ICESat stands for Ice, Clouds and land Elevation SATellite. This NASA satellite carried the Geoscience Laser System (GLAS) onboard. This laser system had the ability to measure with a precision of 5 m in horizontal direction and 10 cm in vertical direction (altitude) for a slope below 1 degree.

The laser has a footprint diameter of 70m on the Earth and makes 40 measurements per second. At the speed of 26,000 km/h it is traveling, this translates into one measurement every 170m. The system has been active during 18 one-month measurement campaigns between 2003 and 2009. The trajectories of one campaign in 2008 called L2D are shown in figure 2.2. It is clear that only a small area of entire Tibet is sampled.

The ICESat satellite was retired in 2010 because of technical problems. Its successor ICESat-2 will be launched in 2017 (NASA ICESat website).

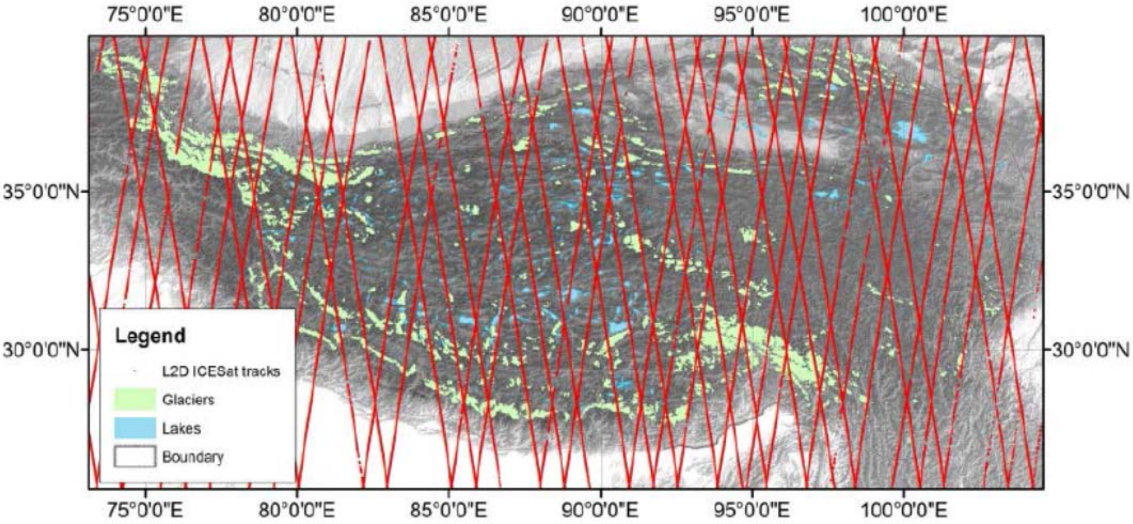

**Figure 2.2: ICESat campaign L2D tracks, lakes and glaciers over one km$^2$ are shown (V.H. Phan et al, 2014).**

Next the way this data was used for glaciers and lakes will be described.

### *Glaciers*

A study was done by Ir. V.H. Phan to find a linear trend for change in glacial thickness for ICESat sampled glaciers. Glaciers had to be observed by ICESat at least 6 times, corresponding to at least 6 ICESat campaigns. For every resulting glacier, the following data was recorded: glacier number, location, orientation and basin. More information was given according to boundary conditions (slope angle in °, slope roughness defined as root mean square to calculate slope plane), number of accepted laser footprints (N), average change per year (v in m/yr), standard deviation of v and root mean square error (RMSE) of v. The boundary conditions were: slope<15 degrees, slope<20 degrees and slope <25 degrees. The roughness had to be below 15m but preferably below 5m. In total 122 glaciers were sufficiently sampled and fell within one or more boundary conditions. Only 122 out of 34,000 is not much, but when considering that the diameter of a sample is only 70m every 170m, that there is a limited number of passes over Tibet every campaign, that the terrain may not be too steep on a mountain and that the glacier has to be observed at least 6 campaigns, this number becomes more understandable.

The boundary condition as used in this research was slope<20 degrees because it contains much more glaciers than the lower boundary condition (<15 degrees) and is more accurate than the higher boundary condition (<25 degrees). The file containing 122 glaciers is the Supplement of: 'Orientation dependent glacial changes at the Tibetan Plateau derived from 2003–2009 ICESat laser altimetry' (V.H. Phan et al, 2014).

### *Lakes*

For the lakes the trend was only recorded if there were at least 4 campaigns and if the observed period was over 2 years (V.H. Phan et al, 2011). The lake information file for lakes contains: lake number, location, basin, name and area. More information was given according to boundary conditions needed to calculate lake level change (distance to outliers when using RANSAC approximation algorithm on ICESat measurements): average change in m/yr and its RMSE. The boundary thresholds are 15cm, 25cm and 35cm for the lake level approximation.

A total of 154 lakes is present in Ir. V.H Phans data file. The boundary condition used for this research is 15 cm, corresponding to the GLAS vertical accuracy as reported in Schutz (2002). The file containing the 154 lakes is from: 'ICESat derived elevation changes of Tibetan lakes between 2003 and 2009' (V.H. Phan et al, 2011).

### 2.2.2. Geometric dependency of Tibetan lakes on glacial runoff

The last data source used here is the paper: 'Geometric dependency of Tibetan lakes on glacial runoff' (V.H. Phan et al, 2012). This paper contains data on the area that contributes water to a lake, (called a sub-catchment area) and the glacier area in this sub-catchment that supplies the lake. Also the glacier area indirectly contributing water to a lake is recorded. This results in a value RD (runoff direct) which is the direct contributing glacier area divided by the lake sub-catchment. The value RU (runoff upstream) is the combined direct and indirect glacier area divided by the lake sub-catchment area.
A high RD value means that a large part of the contributing area for a lake is covered by glaciers. A low RD value means that the contributing area is mostly free of glaciers. When RD is low but RU is high, the lake receives a lot of glacial runoff from upstream lakes.

Figure 2.3 shows a watershed containing two sub-catchments. The left lake has only direct glacial runoff. But the lake on the right has direct and indirect glacial runoff because there is a river flowing from the left to the right lake. For the left lake RD and RU will be the same because there is no indirect glacial runoff. The right lake however has a larger RU value than its RD value because the glacial area for RU is the total glacial area of the entire watershed.

In figure 2.1.E the glaciers and lakes from the different datasets that are present in the area are shown. The glaciers are shown with their orientation and the ICESat lakes with their lake number from Ir. V.H. Phan's paper on elevation changes for lakes. The scale is in degrees (latitude and longitude).

The 'Geometric dependency of Tibetan lakes on glacial runoff' paper is used to see which lakes are more influenced by glaciers than others. In the rest of this paper the term 'geometric lakes' is used when referring to data from 'Geometric dependency of Tibetan lakes on glacial runoff'.

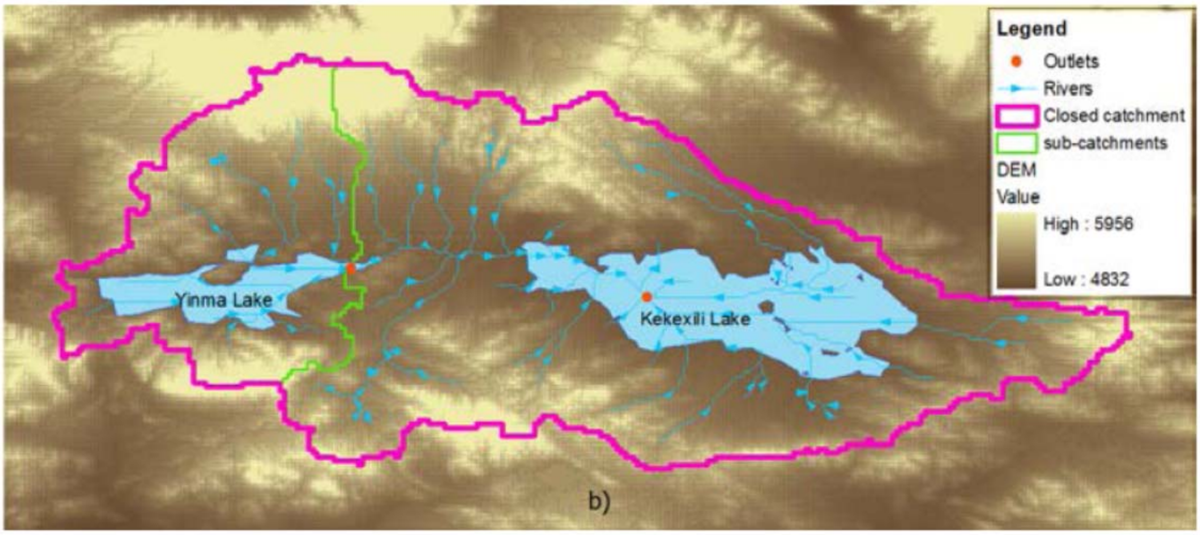

**Figure 2.3: A watershed with two sub-catchments (V.H. Phan et al, 2014)**

# 3. Methods

This chapter discusses the way different factors influencing lake level and glacial thickness changes will be researched. Also the way sampled glaciers and lakes are connected through the flow of glacial runoff, will be looked at.

## 3.1. General analysis

To find out what the relationship is between lake level changes and the dependency on glacial runoff for lakes an analysis between geometric dependency and lake level change is done. Lake level change as function of RD and RU for Tibet as a whole and also some separate regions were looked at.
To find out how altitude influences geometric lake data (RD and RU) and lake level change, these were scatter plotted against each other. This was done by looking at RD, RU and lake level change as a function of altitude in a scatterplot. . To find the influence of altitude on glacial thickness changes the change in thickness as function of altitude was looked at in a scatterplot. This was also done for the different regions where more than four glaciers sufficiently sampled by ICESat were present. Possible relationships can tell something about the changes on the Tibetan plateau as a whole.
If different relationships between regions are found they can help in choosing case studies, which can be used to analyze differences in more detail. Sometimes the different trends might help to explain different ICESat height changes.

## 3.2. Finding the lakes that receive glacial runoff from a glacier

The process of finding the right method to find which ICESat sampled glacier can be linked to an ICESat sampled lake through glacial runoff will be discussed next. This connection is made to compare the influence of glacial thickness change with the lake level change of the lake it supplies with glacial runoff.
Two methods will be discussed: a visual method, showing glaciers and lakes within their watershed boundaries, and a digital method, finding all possible links through watershed ID. The watershed ID is a unique number for every watershed.

### 3.2.1. Preparations

As this research focuses on the influence of glacial changes on lakes, firstly glaciers need to be found where glacial runoff flows to a lake. Both lake and glaciers should be described in V.H. Phans ICESat data files, because for the other glaciers and lakes no height change was recorded.

For this thesis QGIS is used, an open source geographic information systems (GIS). This program provides the ability of data viewing, editing, and analysis. Website: http://www.qgis.org/en/site

To get a topographic map of the entire Tibetan plateau the SRTM tiles for the area between longitude 70-105 °E and latitude 25-40 °N were downloaded and joined in QGIS to get one raster layer. The SRTM raster was rendered in color according to height between 4700 and 5800m with 250m intervals to give the best result for the terrain with the glaciers and the lakes on the Tibetan plateau. Maps that contain the entire Tibetan plateau have every altitude below 2500m rendered white, this was done to get a better idea of the altitude of the Tibetan plateau . The available processed ICESat laser altimetry data was gathered for lakes (V.H. Phan et al, 2011) and glaciers (V.H. Phan et al, 2014) and uploaded to QGIS. In figure 3.1 the generated map is displayed.
The rivers, watershed boundaries, lake and GLIMS glacial mask were downloaded and added in QGIS.

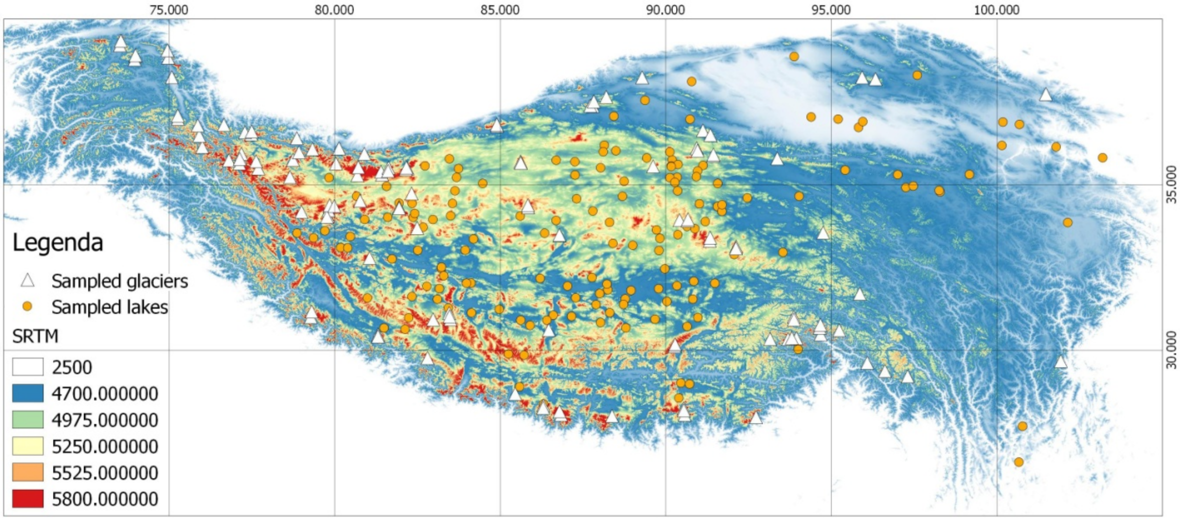

**Figure 3.1: Glaciers and lakes with ICESat data and SRTM With altitude colorization.**

### 3.2.2. First method using geometric lake data

The geometric lake data is useful because it showed which lakes where dependent on glacial runoff and in which amount. If a lake was not mentioned in the geometric lake data file, the lake was not dependent on glacial runoff. The lowest dependency was RU=0.0001, meaning almost no dependency on glacial runoff for the lake. The highest dependency recorded was RD&RU=0.7492, meaning a glacier lake is situated directly below a glacier and receiving its glacial runoff from that glacier. With the geometric lake data in QGIS it is easy to see which lakes can be ignored (no glacial runoff) and which are promising (lake with geometric data).

Because only the height changes for the lakes with ICESat data are known, the lakes with geometric data are only useful if they were also described in the ICESat data file.

If a lake contained ICESat and Geometric lake data the problem was that the markers were not exactly on the same place. This made it impossible to determine if two different markers were in one and the same lake (except when the lake name was recorded in both data files, but this was not often the case).
It was necessary to find out whether ICESat and Geometric data belong to the same lake. The data from 'Geometric dependency of Tibetan lakes on glacial runoff was analyzed with MATLAB to find overlap in lakes with the ICESat lake data. First a program file in MATLAB looked for the closest geometric lake to every ICESat lake. The distance to the closest lake was calculated and if the distance was smaller than 1109 meter[1] (both locations are in the same lake) the lake dominated by glacier info was added behind the ICESat data. The resulting new file included all the ICESat lakes, 67 of which also had geometric data. Not all the lakes with ICESat data have geometric data because not all of them are in a catchment with glaciers (If value of RD&RU=0, no lake dominated by a glacier is recorded). The new dataset will be referred to as *combined lake data*.
This combined lake data is added in appendix A.

With the combined lake data and SRTM layer finding a link between a sampled lake and glacier is still difficult. This is because only 122 glaciers out of about 34,000 and only 67 lakes out of about 900 (larger than 1km) were sufficiently sampled. Also a lake can be in a different watershed than a glacier or a river transports water to another location.
Adding the watershed boundaries in QGIS makes finding connections easier because glaciers and lakes have to be in the same watershed to be linked (water does not flow up hill).

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[1] Search parameter distance was 0.01 degrees this is about 1109 m.

Finding connections between a lake and a glacier for the lakes with the highest RU value from the combined lake data (67 lakes) showing the watershed boundaries and different labels is easier. The labels for the glaciers are their orientation and the most promising lakes (high RU) are labeled with their lake number and RU value in QGIS.

A piece of the generated map is shown in figure 3.2. Because the watershed boundaries were displayed, no attempts are made to connect glaciers and lakes that were not in the same watershed. And because lakes with a high RU value are more likely to receive glacial runoff from more glaciers, the chance that one of the glaciers contains ICESat data is larger.

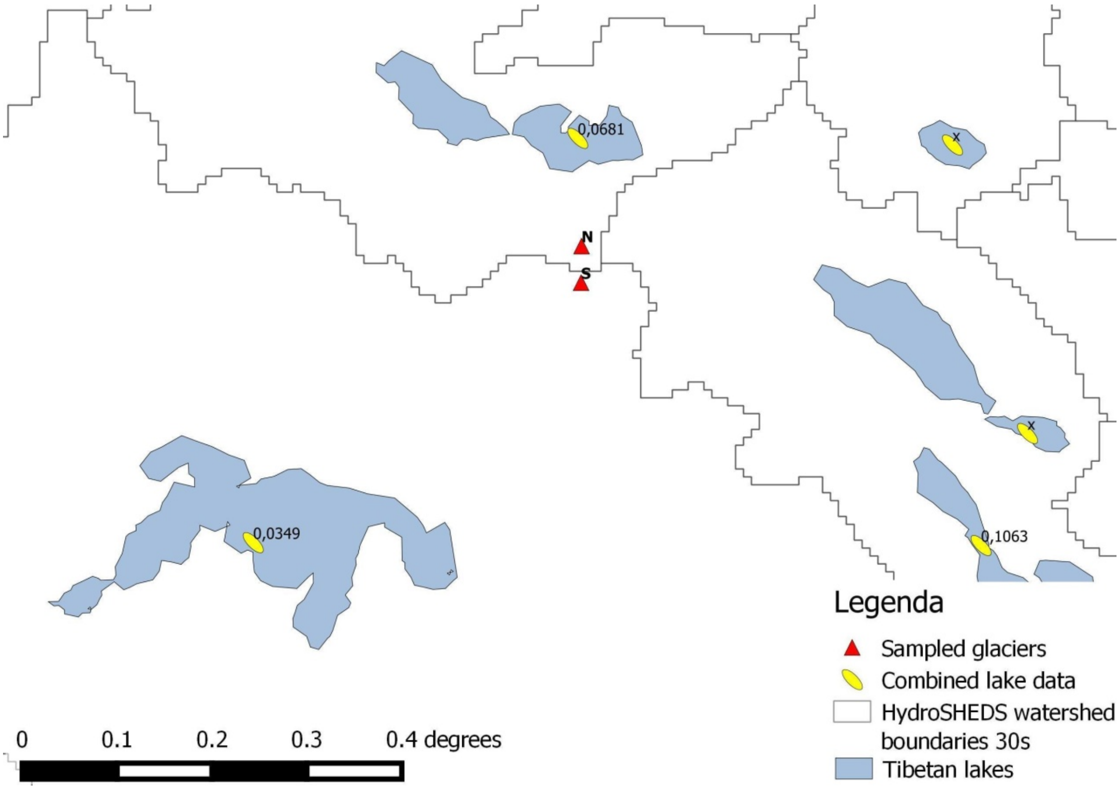


**Figure 3.2: Lake selection with RU value and glacial orientation**

With this method a first selection of possible combinations was made. After this, the SRTM and river data were displayed and a link was either confirmed or denied. Satellite/aerial pictures were also used for final confirmation.

### 3.2.3. Second method using watershed ID

MATLAB was also used to get a more complete picture to find all ICESat glaciers and lakes that were in the same watershed boundary. This was done by first adding the watershed ID for each glacier and each lake from the combined data set to the attribute table by means of a point sampling tool in QGIS. Then the glaciers and lakes were displayed in increasing watershed ID order In MATLAB. Watersheds that contained only glaciers or only lakes were deleted. The watershed ID file after these deletions contains only watersheds that contain both glaciers and lakes, the other watersheds were removed.

# 4. Results

In this chapter the influence of different factors that influence lake level and glacial thickness changes are presented. Also the results of the study on which glaciers and lakes sampled are connected through the flow of glacial runoff are presented.

## 4.1. General results

Figure 4.1 shows a scatterplot of the RD&RU values against the ICESat average height change (m) for the lakes with overlapping data on the Tibetan plateau. The horizontal axis is used to display RD&RU and the vertical axis is used for ICESat lake level change. Most values of RD&RU are between 0 and 0.1 so glacier influence is not very high. RD values are large for small lakes near a glacier. Because only lakes larger than 1km$^2$ have been sampled, most lakes having large RD values are not included in the geometric lake data (and thus not included in this scatterplot). The height change per year is mostly between -0.1 and 0.4 m (see figure 4.1). It is clear that most lake levels are rising.

Figure 4.2 shows the subdivision of Tibet into nine major basins. Inside these basins the watersheds are shown. The inner plateau has many watersheds in its basin. This region has no major rivers leaving its area. The other eight basins have major rivers leaving its area and therefore do not have many watersheds.

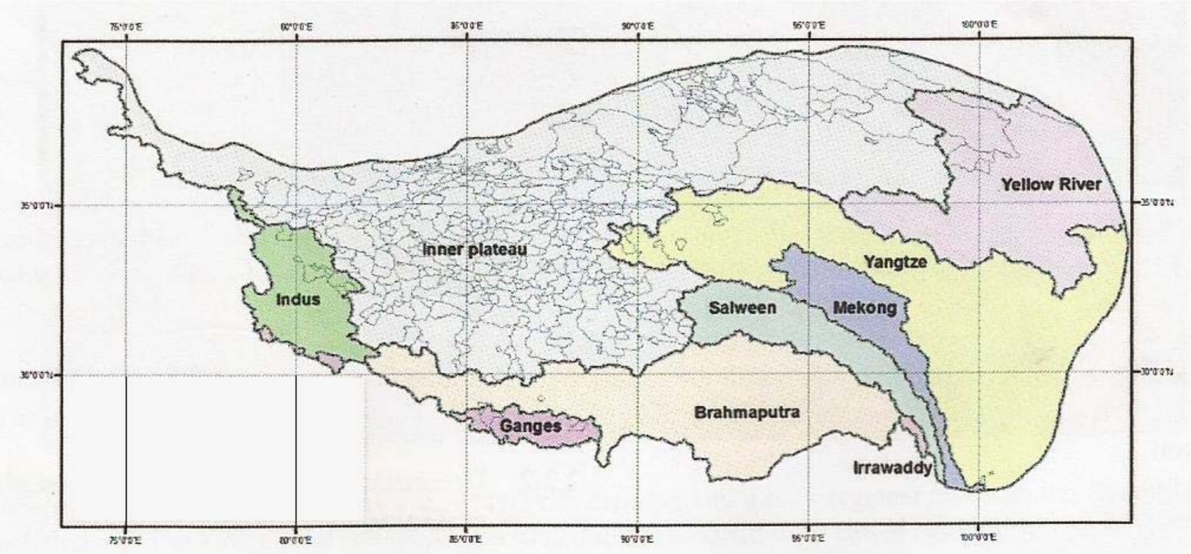


**Figure 4.2: major basins containing watersheds (V.H. Phan et al, 2013)**

Figure 4.3 shows a scatterplot of the height change versus RU for different basins to look for differences between basins. Basins with less than 5 data points are not shown in this figure. For instance the Ganges basin has only 2 data points containing both lake level change and RU value; therefore this basin is not included. The scatterplot gives an indication of what is happening in a basin. For instance, almost all the points from the inner plateau have a positive change (lake level is increasing). But the RU value does not seem to have a big influence.
The problem is that some lakes have a lake level that can't rise because of the topography, e.g. due to outflow at a certain lake level (lake overflows). In chapter 6 this situation and the link between lake level change and the RU value will be discussed.

The change in lake level as function RD and RU (figure 4.1) suggests that the glacial area directly and indirectly supplying a lake does not have much influence on lake level change. That could mean that precipitation changes are dominating lake level changes. This is supported by two things. First of all, Figure 4.3 shows there is an increase in lake level change on the inner plateau, which receives more precipitation due to the partial influence of the Westerlies that are getting stronger. Secondly, lake levels in the Brahmaputra basin are decreasing, while this basin is influenced mostly by the decreasing Indian monsoon (leading to less precipitation).

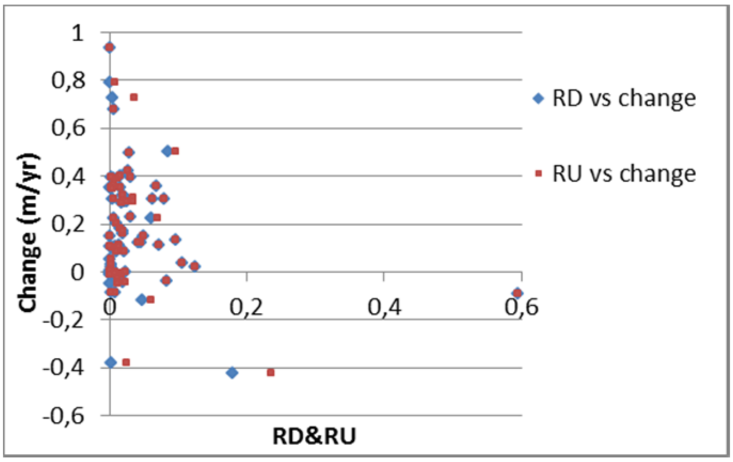
Figure 4.4 shows the correlation between RD&RU values with altitude. From this correlation, the logical conclusion is that lakes at a high altitude are more likely to have a high geometric dependency on glaciers.

More interesting is the correlation between altitude and height change (figure 4.5). The higher the altitude the bigger the lake level increase. The trend is given with the formula and $R^2$ value for lake level change as function of altitude. The glacier scatterplot is more equally distributed and therefore a trend is not shown: some glaciers become higher and others lower over time. This is probably because glacier change will differ for every region depending on weather patterns. The orientation of the glacier also has a big impact on glacier thickness changes.

The difference between regions for lake trends are given in figure 4.6. From this plot it becomes clear that some regions (Inner plateau for instance) have a high annual lake level increase while others (like Brahmaputra ) have an annual lake level decrease.

Figure 4.7 shows the annual change for glaciers in different basins. This can give a rough estimate of the average altitude above which the glacier is getting thicker and below which it could be getting thinner. The combination of figure 4.6 and 4.7 can be used to compare changes in lake level and glacial thickness for the same regions.

Figure 4.4 showed that lake level change has a clear correlation with altitude. However, for glaciers this is less so because of more variables. Looking at different regions for changes in glacial thickness as function of altitude (figure 4.7) a correlation can be seen that is about the same for each region. The point at which this trend line crosses the zero change in thickness is different for each region. This suggests that the average equilibrium altitude is different for each region.



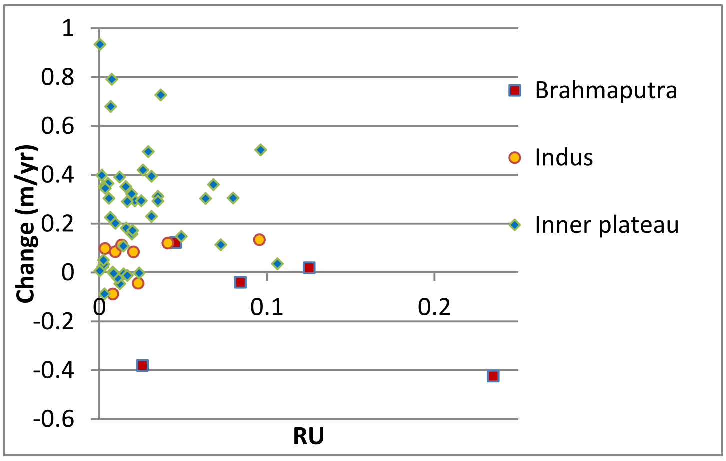
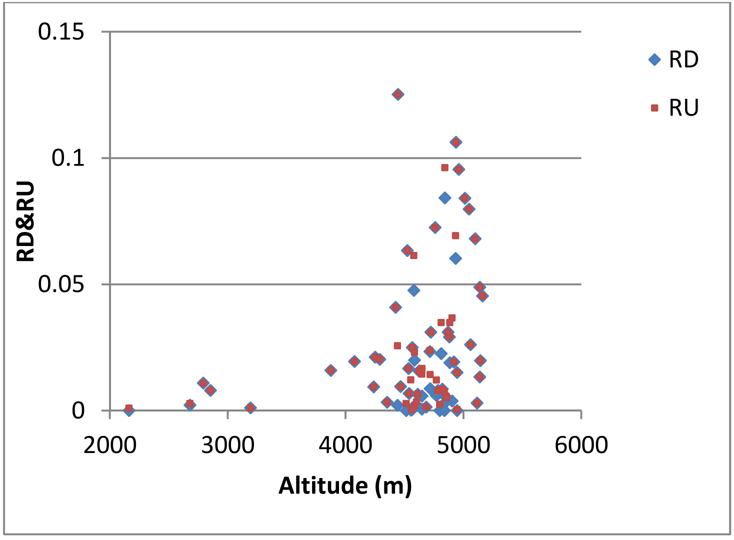


Figure 4.1: Tibetan plateau, RD&RU vs lake change

Figure 4.3: lakes Brahmaputra, Indus& Inner plateau basin, RU vs change



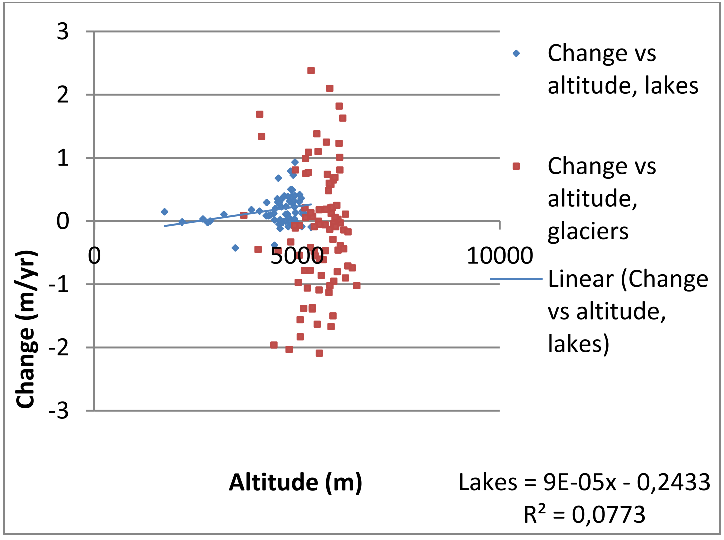
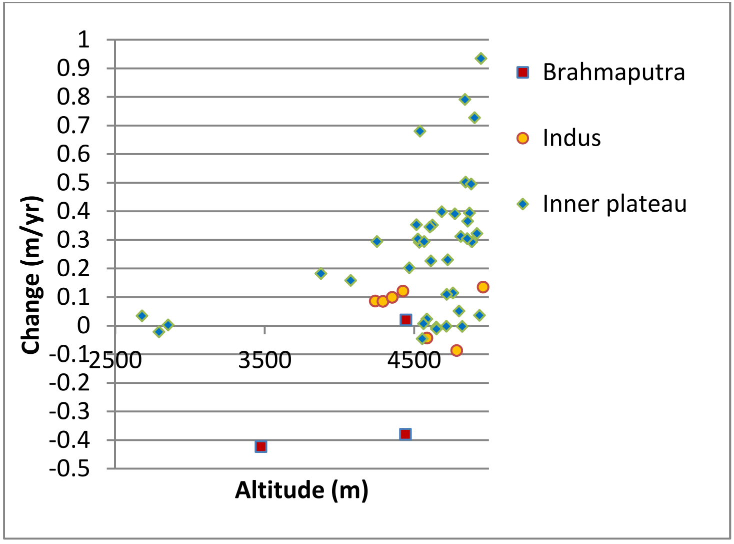


Figure 4.4: RD&RU vs altitude

Figure 4.5: change of glaciers and lakes vs altitude



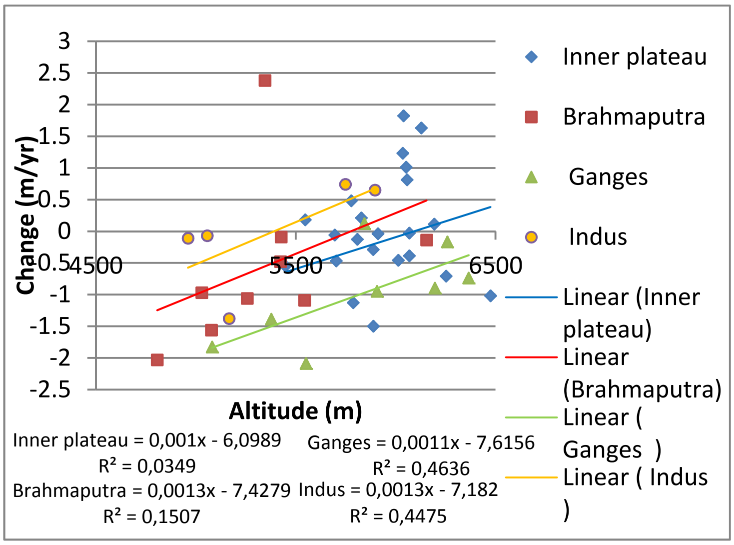


Figure 4.6: changes as function of altitude for lakes

Figure 4.7: Changes glaciers in different basins

## 4.2. Linked glaciers and lakes

The first method (visual inspection) shows combined lake data markers with RU label and sampled glacier markers with label orientation in the watershed boundaries. A visual inspection of this information resulted in ten lake/glacier combinations interesting for possible case studies out of the 67 lakes with sufficient data. Method two (basin ID matching) was used to find all possible combinations of sufficiently ICESat sampled lakes and glaciers. This was done by finding all watersheds that contain both sufficiently sampled lakes and glaciers. Every lake and glacier was given the watershed ID from the watershed they were in and the watershed were ordered in increasing ID value. Watersheds that did not contain a combination of lakes and glaciers were removed. This yielded 25 watersheds that had a combination of glaciers and lakes. From this selection 22 combinations included lakes with geometric lake data. Therefore, these lakes in the watershed were influenced by glacial runoff.

The 10 interesting combinations were found by visual inspection (method 1) and 22 possible combinations were found based on basin ID (method 2). Nine of the visually found combinations (method 1) were also found in the method using watershed ID (method 2). One glacier (nr. 39) from the visual selection was just inside the wrong watershed. I changed the ID number to get the glacier in the right watershed with its corresponding lake. In the discussion chapter this problem will be looked at.

Out of the 22 possible connections, 19 were visually confirmed using satellite photos. One of the connections has problems. The glaciers are on the wrong place on the map (lake 8 and glaciers 29-31). These glaciers and lakes were kept in the final link dataset because at least one glacier is connected to the lake after finding its real location. Figure 4.7 shows all usable lakes and glaciers. In the discussion chapter the problem with lake 8 will be looked at. Appendix B contains the usable lake numbers and glacier numbers for the connected lakes.

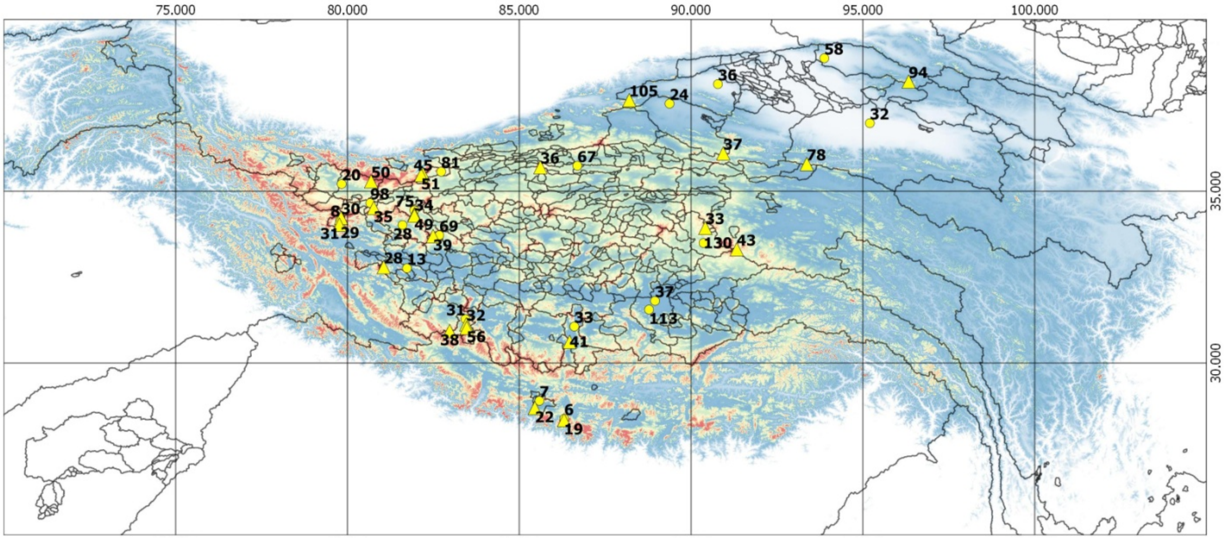


**Figure 4.7: confirmed glaciers connected to lakes**

## 4.3 Selection of case studies

A selection of three case studies were made based on the location, geometric lake data and ICESat measured changes.

The case studies are chosen to show what is happening to glacial thickness and lake levels in different areas and if there is a correlation between the changes. Choosing links in different river basins is a logical choice because the differences in weather patterns on the Tibetan plateau. It is also interesting to look at a location on different sides of climate systems. Also looking at the difference between links with and without outflow might be interesting.

Case study 1: Lake Chin Kul (nr. 20): Aksai Glacier 50 feeding. Inner plateau south side mountain ridge that functions as a climate barrier between the monsoon dominated north side and continental climate dominated south side. This link is interesting to look at because of different glacial changes on both sides of the ridge. For the North side there are only sampled glaciers and no sampled lakes for comparison.

Case study 2: lake Lu Ma Jiang (nr. 28) and Luotuo Lake (nr.75) are both fed by glaciers on the same mountain but from glaciers on different sides. Lake 28 is supplied by glacial runoff from glacier 49 orientated south. Lake 75 is supplied by glacial runoff from glacier 34 orientated north. These lakes and glaciers are also on the Inner plateau. This area is interesting because the mountain is more in the interior of the Tibetan plateau. Therefore it is more influenced by a continental climate and less by the Westerlies. Also because both glaciers have an own lake they influence, a correlation between lake level change and change in glacier thickness can be made. There is also a lake called Qagong Co (nr. 38) which receives no glacial runoff at all. This lake might be used as Control Lake for determination of the effect of glacial runoff.

Case study 3: Lake: Paiku Co (nr. 7) and glacier 22 are located in the Southern part of Tibet in the Ganges basin. This region is interesting because the Indian monsoon is weakening and therefore the precipitation is decreasing. This is the only usable glacier lake combination in the Ganges basin; the other one does not have the ability to sustain a lake level increase after a certain level (this will be discussed in chapter 6: discussion). Also, the lake covers a very large portion of its watershed. The lake is an endorheic lake so it has the ability to sustain lake level rise and fall.

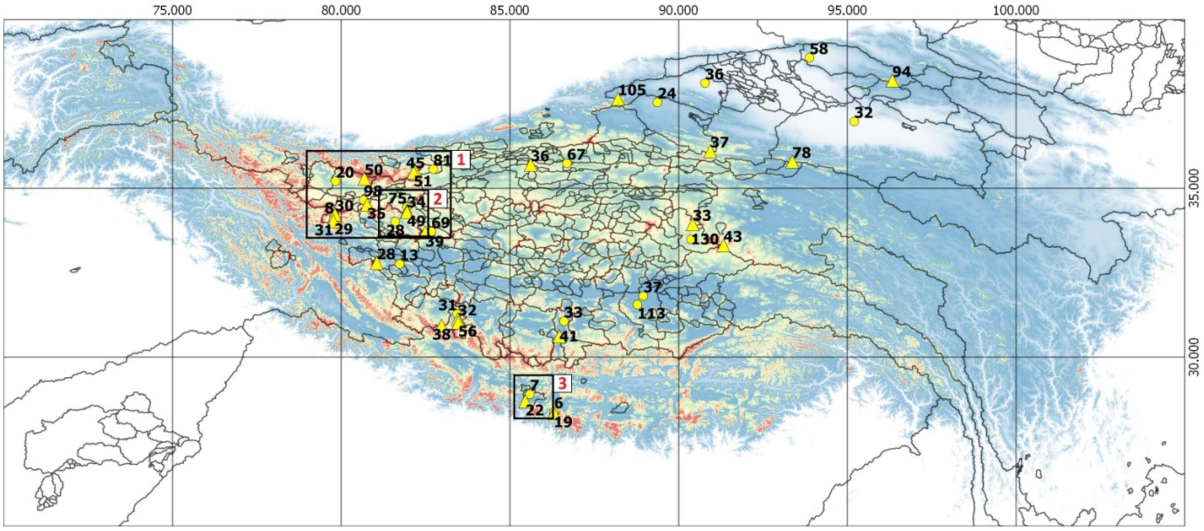


**Figure 4.8: Locations of the three case studies, number of case study in red**

## 5. Case studies

In total 3 case studies were done. The goals were to look at change in glacial thickness and lake level change and determine if there is a correlation. Also the general changes in the region of the case study are looked at.

The selected case studies are worked out in this chapter. They are supported by images of the situation in QGIS and the available ICESat and geometric data.

### 5.1. Case one: Glacier 50 feeding Lake Aksai Chin (nr. 20).

Glacier 50 is located 35.2841°N, 80.6850°E and is a tributary glacier feeding a larger glacial system. It feeds a main glacier to the West. The highest point of the glacier is 6460 m and the lowest point is at circa 6000m. The glacier has an area of only 0.57km$^2$. This glacier meets another main glacier in the valley, this produces the V shape directly below the glacier on the map. The total length of the mountain chain with glaciers is 90km orientated South. All the rivers that result from these glaciers directly or indirectly end up in lake Nr. 20. This lake only has rivers flowing into it and none leaving it; it is an endorheic lake (sink). Figure 5.1 shows the glaciers and lakes for this case study.

The values for the glaciers that are on the same mountain ridge as glacier 50 are given in table 5.1. In this table N, v and RMSE are described in chapter 2 (2.2.1.), q is the standard deviation of the annual change and k is the ratio between glacial area sampled by ICESat footprints and the total glacial area. The lake data for lake 20 and lake 81 are also in table 5.1. Glacier 50 and lake 20 are underlined.

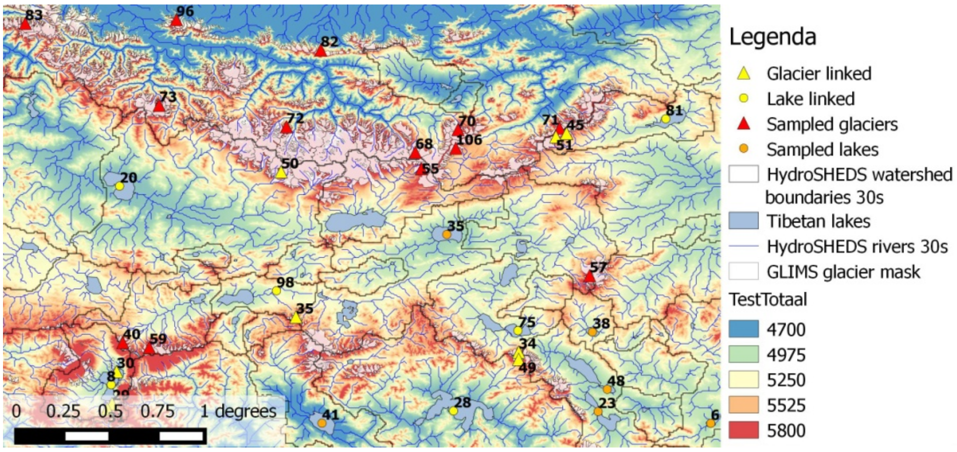
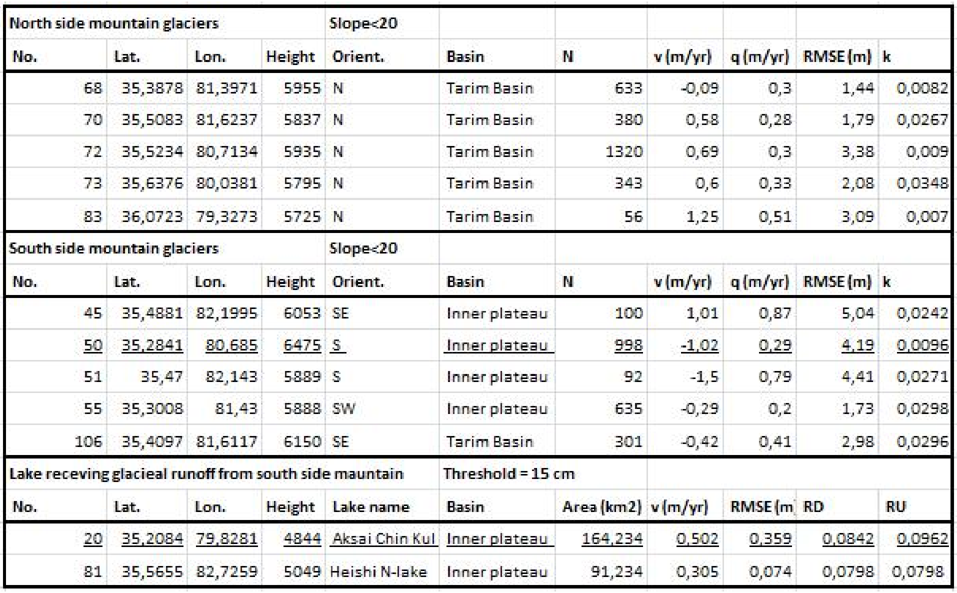


**Figure 5.1: Location case studies one and two, the scale is in degrees.**



| North side mountain glaciers | | | | Slope<20 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Height | Orient. | Basin | N | v (m/yr) | q (m/yr) | RMSE (m) | k |
| 68 | 35,3878 | 81,3971 | 5955 | N | Tarim Basin | 633 | -0,09 | 0,3 | 1,44 | 0,0082 |
| 70 | 35,5083 | 81,6237 | 5837 | N | Tarim Basin | 380 | 0,58 | 0,28 | 1,79 | 0,0267 |
| 72 | 35,5234 | 80,7134 | 5935 | N | Tarim Basin | 1320 | 0,69 | 0,3 | 3,38 | 0,009 |
| 73 | 35,6376 | 80,0381 | 5795 | N | Tarim Basin | 343 | 0,6 | 0,33 | 2,08 | 0,0348 |
| 83 | 36,0723 | 79,3273 | 5725 | N | Tarim Basin | 56 | 1,25 | 0,51 | 3,09 | 0,007 |
| South side mountain glaciers | | | | Slope<20 | | | | | | |
| No. | Lat. | Lon. | Height | Orient. | Basin | N | v (m/yr) | q (m/yr) | RMSE (m) | k |
| 45 | 35,4881 | 82,1995 | 6053 | SE | Inner plateau | 100 | 1,01 | 0,87 | 5,04 | 0,0242 |
| 50 | 35,2841 | 80,685 | 6475 | S | Inner plateau | 998 | -1,02 | 0,29 | 4,19 | 0,0096 |
| 51 | 35,47 | 82,143 | 5889 | S | Inner plateau | 92 | -1,5 | 0,79 | 4,41 | 0,0271 |
| 55 | 35,3008 | 81,43 | 5888 | SW | Inner plateau | 635 | -0,29 | 0,2 | 1,73 | 0,0298 |
| 106 | 35,4097 | 81,6117 | 6150 | SE | Tarim Basin | 301 | -0,42 | 0,41 | 2,98 | 0,0296 |
| Lake receving glacieal runoff from south side mauntain | | | | | Threshold = 15 cm | | | | | |
| No. | Lat. | Lon. | Height | Lake name | Basin | Area (km2) | v (m/yr) | RMSE (m | RD | RU |
| 20 | 35,2084 | 79,8281 | 4844 | Aksai Chin Kul | Inner plateau | 164,234 | 0,502 | 0,359 | 0,0842 | 0,0962 |
| 81 | 35,5655 | 82,7259 | 5049 | Heishi N-lake | Inner plateau | 91,234 | 0,305 | 0,074 | 0,0798 | 0,0798 |

**Table 5.1: Information on glaciers and lakes in the area of case study one**

Glacier 50 is shrinking fast, 1m annually (Table 5.1). Compared to other glaciers in the dataset this is quite much for a glacier at an altitude of 6475 m which is above the ELA's for the region (figure 1.1) and also above the average trend of decline from figure 4.7 for the inner plateau. The large decline is even more striking, when one considers that glacier 72 and 73 on the North side of the ridge are growing half a meter a year (and are located at the same height or lower). Figure 5.2 contains a scatterplot containing all the lakes and glaciers from table 5.1. This figure shows that most glaciers on the North side are growing and on the South side are shrinking. The lakes (nr. 20 & nr. 81) are fed by the glaciers on the South side of the ridge and consequently the water level is rising there.

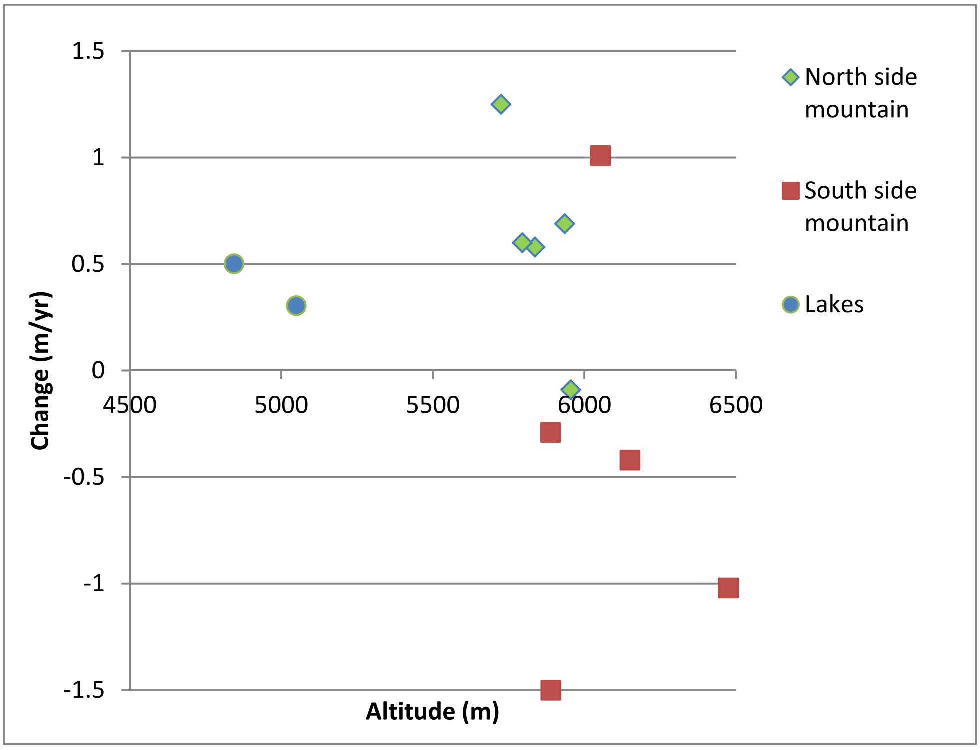


**Figure 5.2: Change as a function of altitude for glaciers and the lakes in the area of case study one**

**Interpretation:**
The Westerlies that are getting stronger and therefore there is more precipitation. This might well be the cause of the growth of the North side of the mountain range. The South side is less influenced by the Westerlies because the mountain range acts as a barrier. The South side is more influenced by a continental climate and climate change.
While the glaciers on the South side are shrinking, the lake level is rising (for both lakes). This might well be because of glacial runoff.

The ICESat data for the glaciers gives a good indication of what is happening in the area. It is a pity that there is no lake near the other two lakes that is not influenced by glaciers.
If there were such a lake, its height level change could be used as a reference and by comparing it to lakes 20 and 81, this could indicate which contribution glacial runoff has on the water level in lakes 20 and 81.

## 5.2. Case two: Glaciers 34 and 49 with lakes 28 and 75 and control lake 38

This case study contains one mountain with one ICESat sampled glacier on the North side and one in the South. Both glaciers have their glacial runoff flowing into an ICESat sampled lake. For the North glacier with nr. 34 this is the lake with nr. 75. For the South glacier with nr. 34 this is the lake with nr. 28. There is also one ICESat sampled lake in the area that is not dependent on glacial runoff and this lake with nr. 38 is used as a control lake. The situation is shown in figure 5.3.

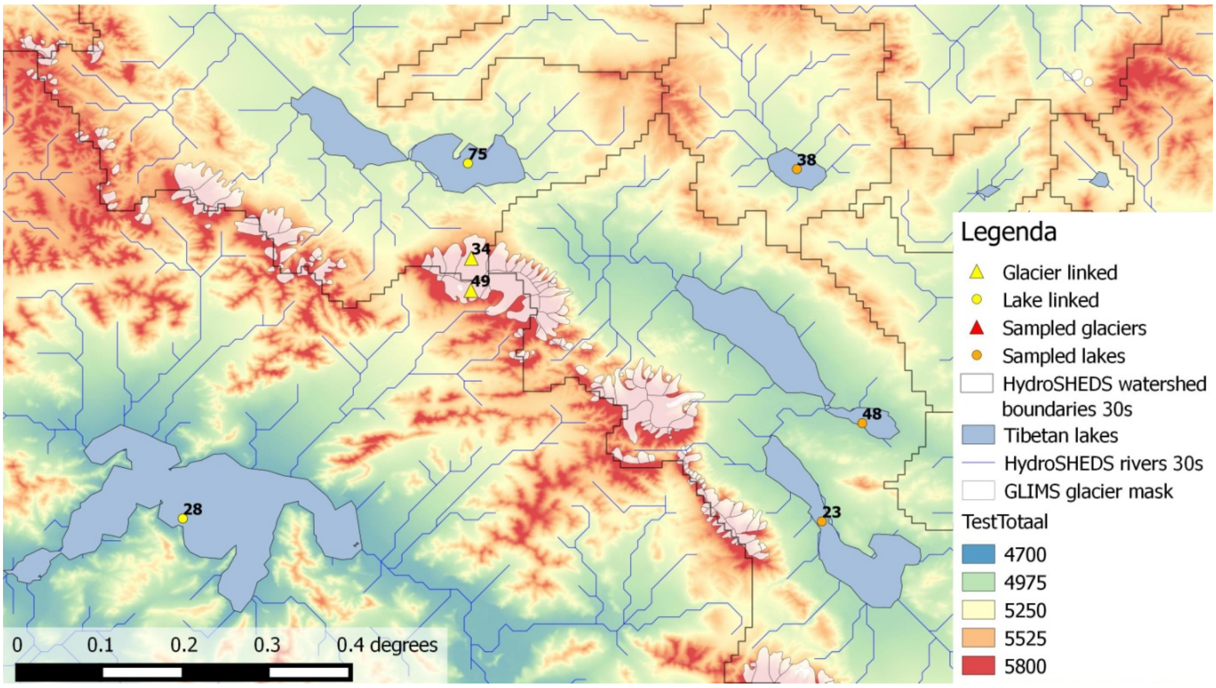


**Figure 5.3: location case study two**

Both glaciers are primary glaciers but glacier 49 might have been a tributary glacier in the past when glaciers covered a larger area. This possible situation is shown in figure 5.4. The black line gives the possible glacial boundary, the big white arrow the main glacier, and the smaller white arrow the potential tributary glacier. Glacier 34 has an area of 14.55 km$^2$,the highest point is about 6350m and the lowest point about 5540m. Glacier 49 has an area of 3.69 km$^2$, the highest point is about 6225m and the lowest point about 5730m. More information about the glaciers is presented in table 5.2. The lake data for lake 28, 75 and also control lake 38 are also in table 5.2. Control lake with number 38 is underlined.

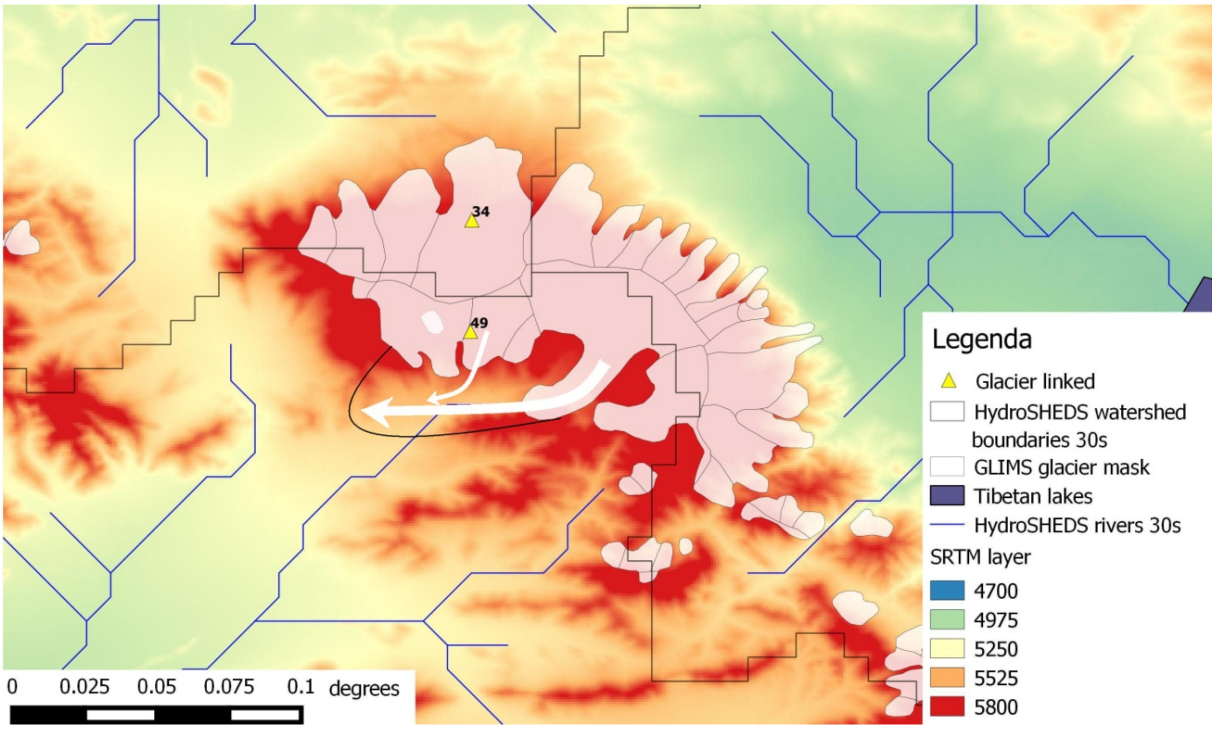
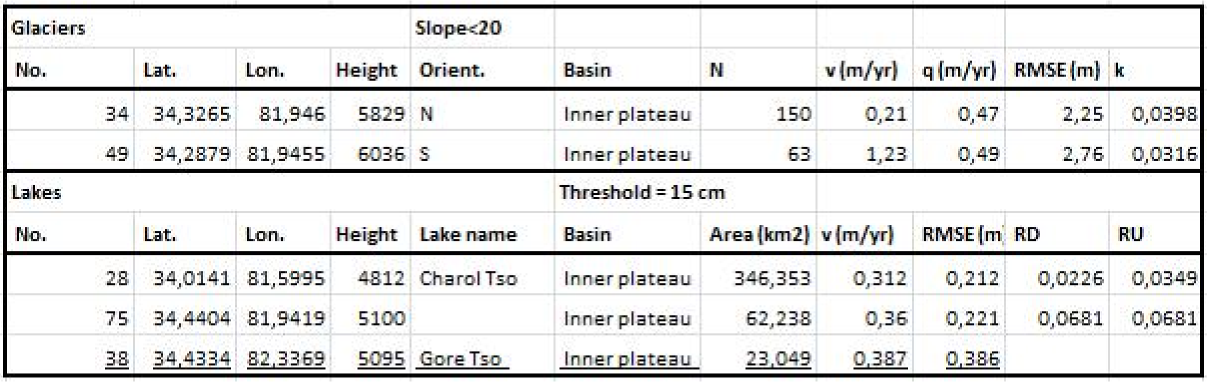


Figure 5.4: Glacier 49 and its possible past as tributary glacier



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Glaciers | | | | Slope<20 | | | | | | |
| No. | Lat. | Lon. | Height | Orient. | Basin | N | v (m/yr) | q (m/yr) | RMSE (m) | k |
| 34 | 34,3265 | 81,946 | 5829 | N | Inner plateau | 150 | 0,21 | 0,47 | 2,25 | 0,0398 |
| 49 | 34,2879 | 81,9455 | 6036 | S | Inner plateau | 63 | 1,23 | 0,49 | 2,76 | 0,0316 |
| Lakes | | | | | Threshold = 15 cm | | | | | |
| No. | Lat. | Lon. | Height | Lake name | Basin | Area (km2) | v (m/yr) | RMSE (m | RD | RU |
| 28 | 34,0141 | 81,5995 | 4812 | Charol Tso | Inner plateau | 346,353 | 0,312 | 0,212 | 0,0226 | 0,0349 |
| 75 | 34,4404 | 81,9419 | 5100 | | Inner plateau | 62,238 | 0,36 | 0,221 | 0,0681 | 0,0681 |
| 38 | 34,4334 | 82,3369 | 5095 | Gore Tso | Inner plateau | 23,049 | 0,387 | 0,386 | | |

Table 5.2: Information on glaciers and lakes in the area of case study two

The interesting situation in this case study is that the thickness change for the glaciers is the opposite of case study one. In this case the change for the Southern glacier is larger than the change in thickness for the Northern glacier. The Northern glacier with number 34 is getting thicker at a rate of +0.21m/yr and the Southern glacier is changing at a rate of +1.23 m/yr.

Recall that in case study one there were only lakes on one side of the mountain, in this case study there is a lake on both sides and also a control lake.
The RU value for lake 75 (RU=0.0681) is almost twice that of lake 28 (RU=0.0348).
The lake level change is positive for all three lakes and very similar with an annual increase of between 31.2cm and 38.7cm.

**Interpretation:**
All the lakes and glaciers in this case study have increased in level. This means that the precipitation must have increased or the outflow from lakes and evaporation must have decreased due to a decrease of temperature. But because of the average temperature increase of 1.8 °C since 2006 (B Wang et al, 2008), a decrease in temperature is less likely than an increase in precipitation.

The difference in glacial thickness change between the glaciers is more than 1 meter. But the glacier thickness is increasing the most on the southern glacier which is located 207m higher than the other glacier. If the trend found in figure 4.7 is used, this difference in altitude translates in a difference of 0.207m (0.001 change (m) per meter × 207meter=0.207m) of extra glacial thickness change and not more than a meter. This theoretical difference of about 20cm is far away from the ICESat difference of more than a meter. The fact that there is only one glacier on both sides and the standard deviation for both measurements is between 0.47 and 0.49m might be one reason for the large difference.
The change in lake level between the fastest and slowest increasing lake level is 7.5mm.
This is not enough to explain glacial change. It only makes an increase in precipitation more likely.

It is important to understand the difference between case study one and case study two. In case study one the glaciers on the North side are getting thicker and the glaciers on the South side are getting thinner. However in case study two it is the other way around, the North side decreases and the South side increases. This might suggest that the mountain ridge might be acting as a climate barrier as suggested in case study one.

## 5.3. Case three: Glacier 22 and lake Paiku Co, nr.7

Most links between glaciers and lakes are found in the Inner plateau. This case study will address a watershed in the Ganges basin. This watershed is trapped in the very large watershed containing the Ganges river. Figure 5.5 shows the location of this case study.

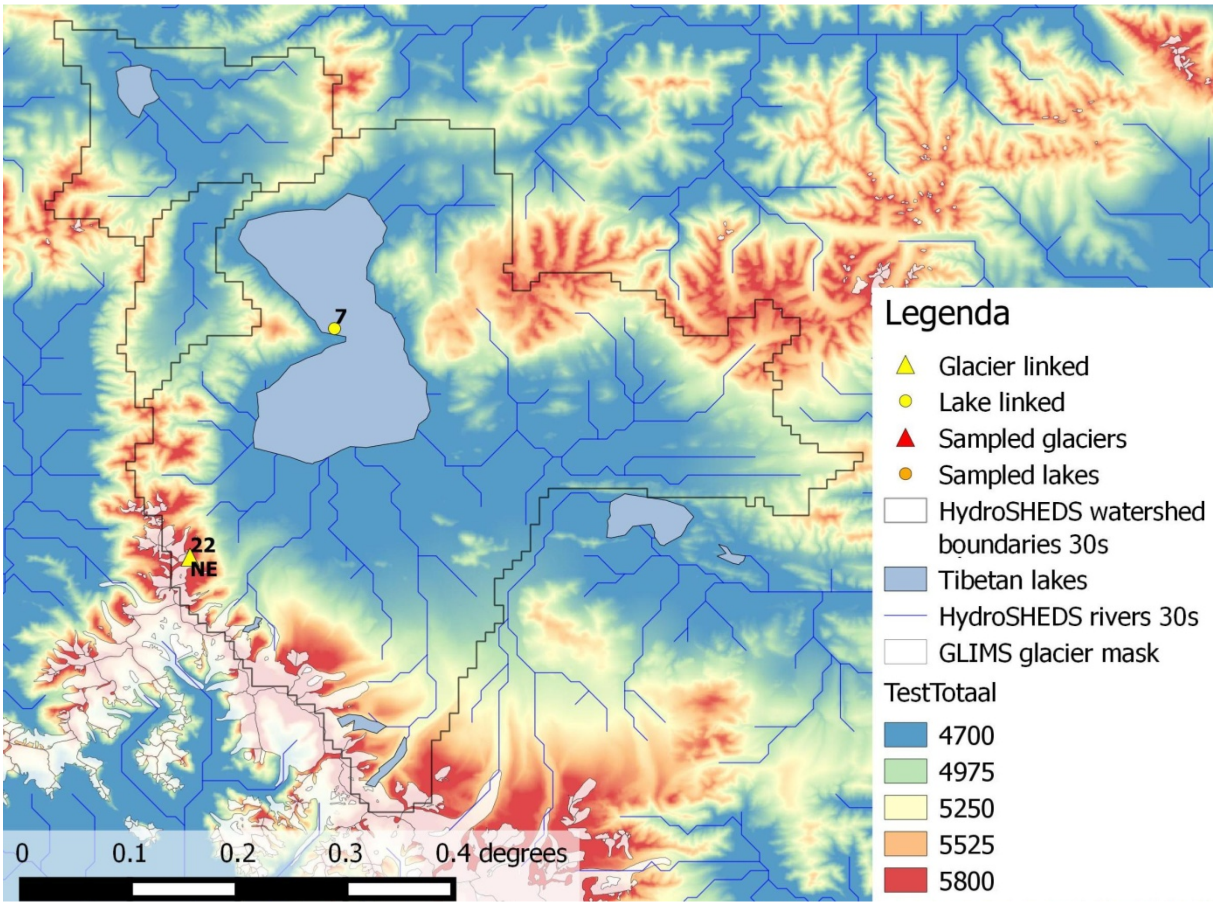


**Figure 5.5: location case study three**

Glacier 22 is a small glacier of only 0,7 km$^2$ and has only ICESat glacial thickness data when the boundary condition is raised from an maximum angle of 20 to 25 degrees. The glacial runoff goes to lake 7 which is a endorheic lake (sink). Glacier and lake information are shown in table 5.3. One interesting thing to mention is that the lake covers a large portion of the watershed. About 10.2% is covert by the lake. So far the highest other ratio found was 6.4% which is also already very high. These percentages are derived from lake area and watershed area in from data sources in QGIS. One other thing to mention is that both the lake level and glacier thickness are declining.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Glaciers | | | | Slope<25 | | | | | | |
| No. | Lat. | Lon. | Height | Orient. | Basin | N | v (m/yr) | q (m/yr) | RMSE (m) | k |
| 22 | 28,6863 | 85,4509 | 6013 | NE | Ganges | 70 | -0,39 | 0,36 | 6,9 | 0,0117 |
| Lakes | | | | | Threshold = 15 cm | | | | | |
| No. | Lat. | Lon. | Height | Lake name | Basin | Area (km2) | v (m/yr) | RMSE (m) | RD | RU |
| 7 | 28,8982 | 85,5849 | 4580 | Palku Tso | Ganges | 276,602 | -0,118 | 0,259 | 0,0476 | 0,0614 |

**Table 5.3: Lake and glacier data for case study three**

**Interpretation:**

Because both the glacier thickness and lake level are declining it is interesting to know if the same thing is happening in the surrounding area. Figure 5.6 shows a larger area and includes additional glaciers. No lakes were present in the direct area around the case study because the river basins do not contain many sampled lakes. The information for the additional glacier is given in table 5.4.

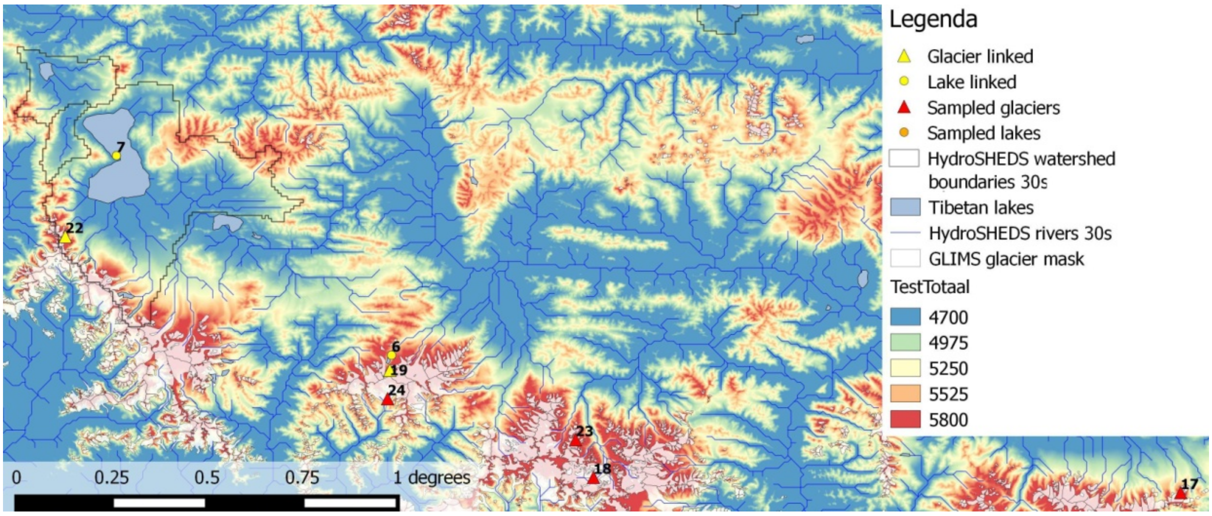


**Figure 5.6 larger area around case study 3**

| Other glaciers in the area | | | | | | Slope<20 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Height | Orient. | Basin | N | v (m/yr) | q (m/yr) | RMSE (m) | k |
| 17 | 28,0152 | 88,3758 | 5907 | N | Ganges | 61 | -0,95 | 0,81 | 2,63 | 0,0239 |
| 18 | 28,0554 | 86,8359 | 5552 | N | Ganges | 239 | -2,09 | 0,36 | 7,61 | 0,0115 |
| 19 | 28,336 | 86,3018 | 5844 | N | Ganges | 93 | 0,12 | 0,25 | 4,64 | 0,0129 |
| 23 | 28,154 | 86,789 | 6259 | E | Ganges | 74 | -0,17 | 0,52 | 2,97 | 0,011 |
| 24 | 28,2613 | 86,2958 | 5082 | S | Ganges | 323 | -1,83 | 0,37 | 3,4 | 0,0283 |

**Table 5.4 additional glaciers information**

The additional data confirms that all glaciers with one exception are decreasing. Figure 4.7 also gives information that supports a general glacial thickness decline. The increase in temperature and decrease in precipitation from the Indian monsoon are affecting the glaciers as a result they are getting thinner. The lake level is not rising by glacial runoff because the influence is too small compared with the decrease of precipitation.

The influence of precipitation is dominant compared with glacial runoff for lake level change.

# 6. Discussion

Problems found in previous chapters will be discussed and where needed illustrated.

## 6.1. HydroSHEDS

The different types of HydroSHEDS problems encountered will be discussed.

### 6.1.1. HydroSHED failed to correctly find river and watershed boundary.

The HydroSHED layers are made using SRTM data, that are not very accurate - only within 16 m for mountainous terrain (Zandenberg, 2008). Since watershed and river network data are derived from this, they include mistakes.

In figure 6.1 lake 98 (location: 34.6523°N, 80.6606°E) is shown. According to the (calculated) HydroSHED river network this lake is not connected to the lake in the East.

But when looking on satellite data, one will see that there is a river connecting these lakes. In the satellite picture below, a blue line is added to make the river more visible. Due to the presence of the river connecting lake 98 and the lake to the East, the watershed boundary between the lakes should not exist. The lakes should be in the same watershed.

To the West of lake 98, there is a big lake that is connected according to the river network. But this time this is not the case. When looking on satellite pictures, one will see a very small lake West of lake 98 that is not connected to it. This very small lake has a river flowing to the big Western lake (not lake 98). There might be a seasonal connection between lake 98 and the lake to the west but this is not visible on the satellite photos.

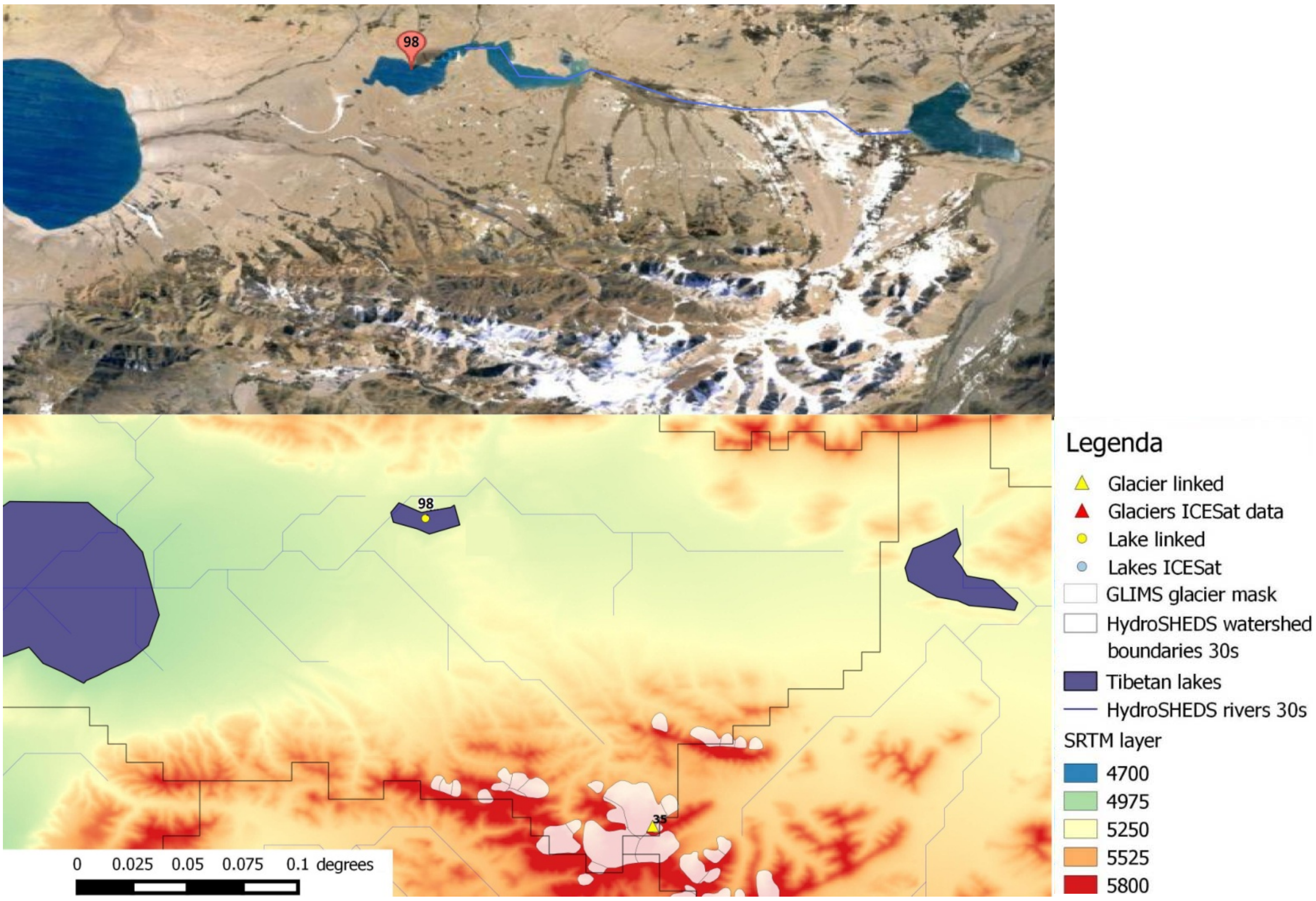


**Figure 6.1: Rivers and boundary wrongly placed**

### 6.1.2. Watershed boundary problems

When comparing the lakes and glaciers that were found to be connected in chapter 3 using method 1, with those found with method 2, there was one connection that was not found by method 3. This was because the glacier, on the border of a watershed, was wrongly placed in the neighboring watershed. The glacier discussed is glacier 39 and is displayed in figure 6.2.
The watershed boundary vector file used as shown in black was made in a 30 arc-second resolution (about 870m for Tibet). And therefore the boundary was so inaccurate that the glacier was placed in the wrong watershed.
Later a boundary vector file shown in red with a resolution of 15 arc-second was used. Now the glacier is in the right watershed. The glacier is still partly in the wrong watershed.

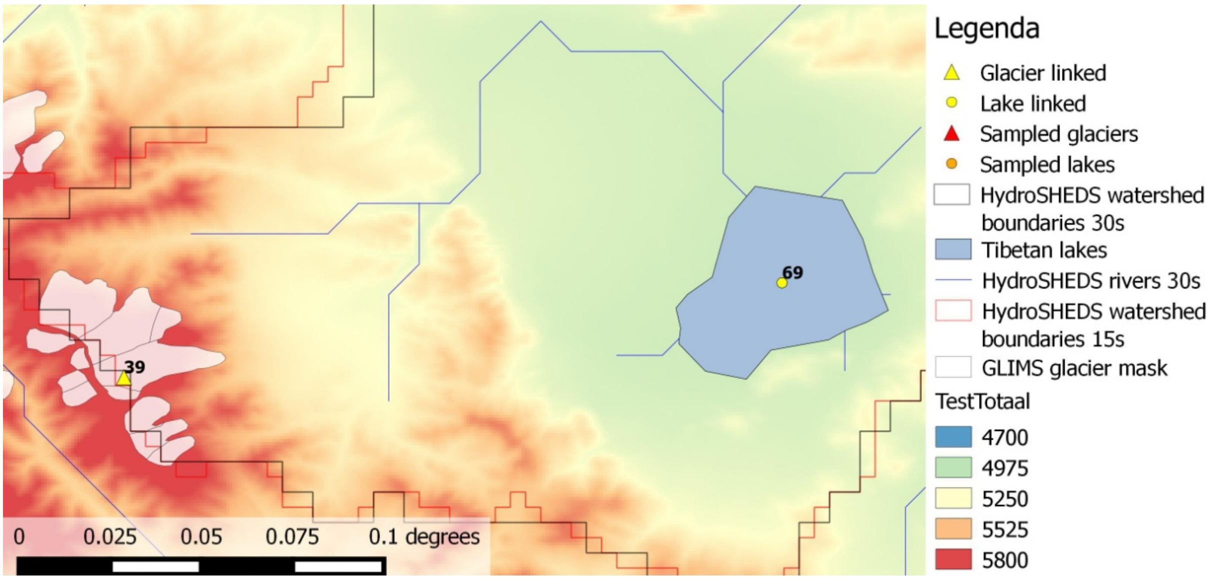


**Figure 6.2: hydroSHED boundary problem**

## 6.2. GLIMS glacier mask

Near lake 8 the glaciers are on the wrong place on the map. To illustrate this, the situation is shown in figure 6.3, with the right place of the glaciers on satellite pictures and some misplaced glaciers in the QGIS picture. Some glaciers are shown on the lake and others are clearly off-center. Glacier markers 29-31 are from the ICESat data file and are also placed on top of the misplaced glaciers. In figure 6.3, arrows show where some of the misplaced glaciers should be. After relocation, only glacier 30 contributes to lake 8.

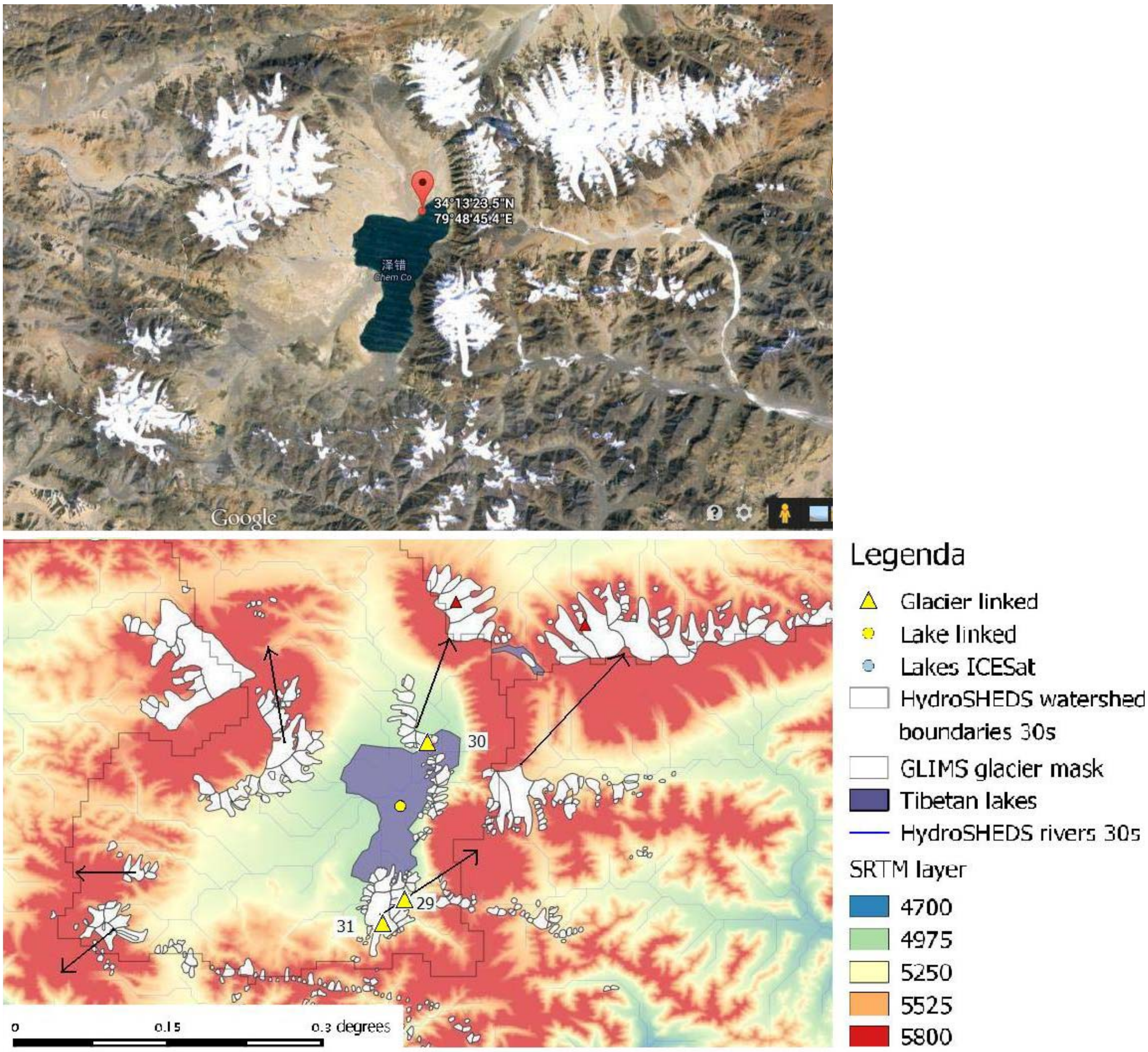


Figure 6.3: Glacial mask and ICESat marker errors

## 6. 3. Glaciers dominated by glaciers

The geometric lake data has some limitations in combination with ICESat lake level changes. There seem to be two problems. One the lake size is not taken into account and secondly the lakes sometimes overflow and therefore the lake level can’t rise above a certain level.

### 6.3.1. RD&RU and lake size

Comparing lake level change with RD&RU can give a distorted representation. This is the case because RD & RU are not dependent on lake size. For instance, when lake A has a lake level change of 1 meter and lake B, that has half the area of lake A, receives the same volume of water as lake A, the water level in lake B will rise 2 meter. A suggestion for the use of ICESat lake level change in combination with geometric lake data is given in chapter 8.

### 6.3.2. Lakes and outflow

The problem is that a lake with a very high RD value (and thus a high RU value) is probably very close to a glacier and therefore on the mountain side. This means that the lake can’t increase in height very much: it will overflow to the valley.

So the change in water level is very much influenced by lake outflow. It would be better to only compare lakes with limited or no outflow. This would influence the trends very much, because the lake levels have the ability to rise and fall. For instance lake 6 has an RD and RU value of about 0.6 and the lake level drops 92 mm/yr. Figure 6.4 shows the location of lake 6 and a profile of the lake on the mountain. The course of the profile is displayed as a black line on the map. Below the area of the lake a blue line has been drawn. After this line there is only a very small boundary that can’t contain a large lake level increase. And the annual lake level decrease might be caused by the deepening of the river channel leaving the lake.

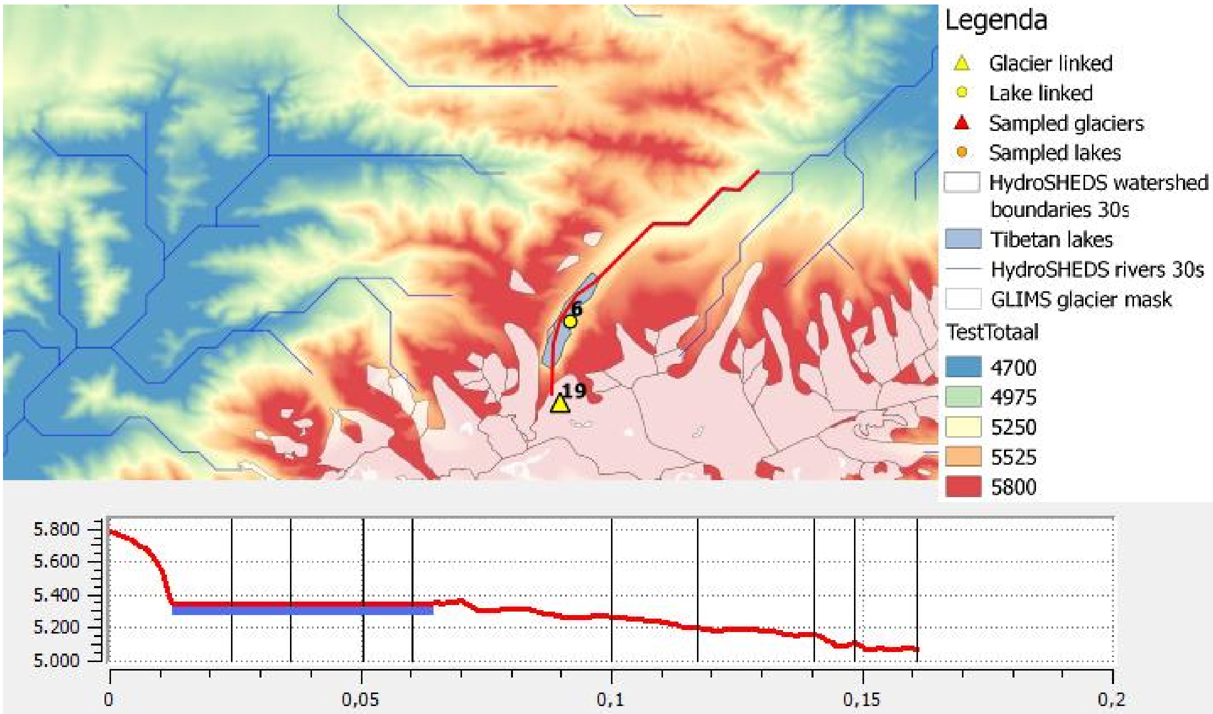


**Figure 6.4: Lake 6 and the lake of possibility of lake level change (profile height in m and distance in degrees)**

## 7. Conclusion

In this bachelor thesis the connection between glaciers and lakes selected by Ir. V.H. Phan are researched, especially the correlation between lake and glacial vertical changes. ICESat height change measurements and processed data about lakes water supply were used.

Out of the approximately 34,000 glaciers in Tibet, 122 glaciers were sufficiently sampled by ICESat to determine thickness changes. For the other glaciers there was not enough information available to use them in the research, either due to the limited area which was sampled by the satellite, the need to have at least 6 ICESat satellite measurements over time, and the need of having a glacier mountainside slope of less than 25 degrees. Tibet has 900 lakes with of at least 1 square kilometer. At least 4 campaigns were required per lake over a period of 2 years. In total this results in 154 lakes that are sufficiently sampled by ICESat.

From correlating lake level changes to glacial thickness changes the following conclusions are drawn:

- It is clear that most lake levels are rising in Tibet and that the relative area of glaciers for a watershed (RU value) does not seem to have a big influence on lake level change. The rate of lake level change is different for different regions.
- There is no clear trend in glacial thickness change as function of altitude for the complete area of Tibet, but there is a clear trend for different basins. The difference between different basins can be very large.

In total 19 connections between glaciers and lakes were found. This means that glacial runoff from a glacier sufficiently sampled by ICESat reaches a lake trough the river system and the lake is also sufficiently sampled by ICESat. This is quite a large number of connections. Especially considering the fact that in the great river basins, glacial runoff is often transported out of Tibet through the river systems and no lakes are visited on the way. So no correlation between glacial thickness and lake level change can be made.

To check the results, three case studies were made. Each case study consists of a map of the location, a description of what is happening to the glaciers and lakes in the area and an interpretation of why the changes are happening. The case studies confirmed that glacial runoff probably has only a very small impact on lake level change. So no clear direct correlation between change in glacial thickness and lake level change can be made. Most likely, the change in temperature and weather systems has a much larger impact.
The case studies seem to confirm that the Westerlies are getting stronger which means that there is more precipitation. This is because in the region affected by the Westerlies have an increase in glacial thickness and in lake level. One case study suggests that the Indian Monsoon is decreasing in strength and there for there is less precipitation. This is because in this area the glacier thickness and lake levels are decreasing.

More precipitation seems to means thickening glaciers and an increase in lake level. Less precipitation seems to means that glaciers are getting thinner and lake levels are decreasing. This would suggest that there is an indirect correlation between the change in glacial thickness and lake level change: they both follow the increase or decrease of precipitation.

# 8. Recommendations

In this chapter possible additions and use of other methods are discussed.

## 8.1. The use of only endorheic lakes

To analyse the correlation of glacial thickness and lake level change, it would be better if only endorheic lakes lakes were used. This is because their water level has the ability to rise and decline because of topography. In other words: the lake level decreases when the water it receives flows away through rivers, while it can rise when receiving more water.

## 8.2. Geometric dependency additions

Making geometric dependency dependent on lake size would be interesting, because the amount of lake level change is dependent on the size of the lake. Also calculating what percentage of rainfall will reach the lake depended on terrain might be interesting. It is thus recommended to include a percentage of surface runoff that reaches a lake. This way the impact of glacial runoff might become more apparent.

## 8.3. Effect of orogenesis on derived ICESat results

It would be nice to correlate height changes with changes caused by orogenesis, with respect to glacier and lake level change. Also isostatic rebound might still affect the region. All in all, a true change in glacial thickness and lake level change might be called for.

## 8.4. Volumetric glacial change

Talking about change in length, area or height can give an indication of what is happening but when can one talk about growth or decline? A glacier can be getting smaller in area but the thickness can increase. Creating a model to combine different changes and using this for a change in volume or mass might be called for to gain a greater understanding for glacial change.

## 8.5. Lake level change and erosion

Erosion caused by glacial run-off and surface run-off on the steep terrain is eating away on the terrain. A part of the material moved by erosion will settle in the lake and affect the lake level. The effect might be minimal during the ICESat campains (2003-2009) but when ICESat-2 will be used for a long time it might be interesting to look at the influence of erosion on lake level change.

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# Appendixes

Appendixes from previous chapters are added behind this page.

## Appendix A: Combined lake data

The data from ‘Geometric dependency of Tibetan lakes on glacial runoff was analyzed with MATLAB to find overlap in lakes with the ICESat lake data (datasets described in chapter 2). First a program file in MATLAB looked for the closest geometric lake to every ICESat lake. The distance to the closest lake was calculated and if the distance was smaller than 1109 meter the lake dominated by glacier info was added behind the ICESat data (both locations are in the same lake and search parameter distance was 0.01 degrees this is about 1109 m).

The resulting new file included all the ICESat lakes, 67 of which also had geometric data. Not all the lakes with ICESat data have geometric data because not all of them are in a catchment with glaciers (If value of RD&RU=0, no lake dominated by a glacier is recorded). This combined lake data is added in appendix A.

## Appendix B: Linked lakes and glaciers

Method two (basin ID matching) was used to find all possible combinations of sufficiently ICESat sampled lakes and glaciers. This was done by finding all watersheds that contain both sufficiently sampled lakes and glaciers. Every lake and glacier was given the watershed ID from the watershed they were in and the watershed were ordered in increasing ID value. Watersheds that did not contain a combination of lakes and glaciers were removed. This yielded 25 watersheds that had a combination of glaciers and lakes. From this selection 22 combinations included lakes with geometric lake data. Therefore, these lakes in the watershed were influenced by glacial runoff.

Out of the 22 possible connections, 19 were visually confirmed using satellite photos. One of the connections has problems. The glaciers are on the wrong place on the map (lake 8 and glaciers 29-31). These glaciers and lakes were kept in the final link dataset because at least one glacier is connected to the lake after finding its real location. Appendix B contains the usable lake numbers and glacier numbers for the connected lakes.

## Appendix A: Combined lake data

| ICESat lake data | | | | | Threshold = 15 cm | | | Geometric lake data | | | | | | Height SRTM | WaterSHEDS basin data | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Basin | Lake name | Area km^2 | Change m/yr | RMSE m | No. | Lat | Lon | Lake Name | RD | RU | Altitude m | BASIN_ID | AREA_KM^2 |
| 1 | 30.0257 | 93.9973 | Brahmaputra | Draksum Tso | 25.973 | -0.423 | 1.087 | 9 | 30.026 | 93.997 | Draksum Tso | 0.1784 | 0.2350 | 3475 | 108795 | 1574326.4 |
| 2 | 29.0117 | 90.4565 | Brahmaputra | Gongmo Tso | 39.791 | 0.020 | 0.179 | 24 | 29.012 | 90.457 | Gongmo Tso | 0.1252 | 0.1252 | 4445 | 108795 | 1574326.4 |
| 3 | 28.5596 | 90.3925 | Brahmaputra | Phuma Tso | 283.629 | -0.039 | 0.241 | 29 | 28.560 | 90.393 | Phuma Tso | 0.0841 | 0.0841 | 5013 | 108795 | 1574326.4 |
| 4 | 29.8884 | 85.2471 | Brahmaputra | Trengcham Tso | 7.128 | 0.124 | 0.279 | 12 | 29.888 | 85.247 | Trengcham Tso | 0.0454 | 0.0454 | 5162 | 108795 | 1574326.4 |
| 5 | 28.979 | 90.7171 | Brahmaputra | Yamdrok Tso | 607.186 | -0.380 | 0.568 | 36 | 28.979 | 90.717 | Yamdrok Tso | 0.0021 | 0.0257 | 4442 | 108795 | 1574326.4 |
| 6 | 28.3753 | 86.3064 | Ganges | Lama Tso | 3.721 | -0.092 | 0.278 | 42 | 28.375 | 86.306 | Lama Tso | 0.5951 | 0.5951 | 5346 | 108795 | 1574326.4 |
| 7 | 28.8982 | 85.5849 | Ganges | Palku Tso | 276.602 | -0.118 | 0.259 | 37 | 28.898 | 85.585 | Palku Tso | 0.0476 | 0.0614 | 4580 | 93446 | 2213.6 |
| 8 | 34.1528 | 79.7836 | Indus | Dyap Tso | 113.923 | 0.135 | 0.373 | 47 | 34.153 | 79.784 | Dyap Tso | 0.0955 | 0.0955 | 4961 | 75080 | 1791.1 |
| 9 | 30.6344 | 82.1228 | Indus | Konggyu Tso | 59.907 | -0.087 | 0.272 | 59 | 30.634 | 82.123 | Konggyu Tso | 0.0080 | 0.0080 | 4784 | 105127 | 855044.8 |
| 10 | 30.6725 | 81.4876 | Indus | Mapham Tso | 412.796 | -0.043 | 0.288 | 60 | 30.673 | 81.488 | Mapham Tso | 0.0200 | 0.0231 | 4585 | 105127 | 855044.8 |
| 11 | 33.606 | 79.7017 | Indus | Pang Gong Tso | 441.236 | 0.086 | 0.616 | 61 | 33.606 | 79.702 | Pang Gong Tso | 0.0094 | 0.0094 | 4239 | 105127 | 855044.8 |
| 12 | 33.5384 | 78.8605 | Indus | Pangur Tso | 54.553 | 0.085 | 0.405 | 48 | 33.538 | 78.860 | Pangur Tso | 0.0203 | 0.0203 | 4291 | 105127 | 855044.8 |
| 13 | 32.7559 | 81.7289 | Indus | | 57.847 | 0.121 | 0.232 | 51 | 32.756 | 81.729 | | 0.0409 | 0.0409 | 4425 | 83843 | 3035.7 |
| 14 | 31.5787 | 80.9865 | Indus | | 13.524 | 0.113 | 0.584 | 53 | 31.579 | 80.987 | | 0.0133 | 0.0133 | 5140 | 105127 | 855044.8 |
| 15 | 33.3926 | 79.36 | Indus | | 5.053 | 0.099 | 0.561 | 49 | 33.393 | 79.360 | | 0.0033 | 0.0033 | 4353 | 105127 | 855044.8 |
| 16 | 33.4336 | 80.4694 | Indus | | 3.865 | -0.008 | 0.736 | | | | | | | 4287 | 105127 | 855044.8 |
| 17 | 33.0985 | 80.1782 | Indus | | 6.075 | -0.142 | 0.414 | | | | | | | 4346 | 105127 | 855044.8 |
| 18 | 33.0902 | 80.3916 | Indus | | 13.629 | -0.281 | 0.728 | | | | | | | 4337 | 82263 | 2413.4 |
| 19 | 37.0671 | 88.4306 | Inner plateau | Achik Kul | 354.791 | 0.294 | 0.371 | 76 | 37.067 | 88.431 | Achik Kul | 0.0212 | 0.0212 | 4251 | 53833 | 13187.7 |
| 20 | 35.2084 | 79.8281 | Inner plateau | Aksai Chin Kul | 164.234 | 0.502 | 0.359 | 109 | 35.208 | 79.828 | Aksai Chin Kul | 0.0842 | 0.0962 | 4844 | 61084 | 7991.2 |
| 21 | 32.0229 | 91.482 | Inner plateau | Amdi Tsonak Tso | 187.849 | 0.023 | 0.490 | 235 | 32.023 | 91.482 | Amdi Tsonak Tso | 0.0019 | 0.0019 | 4585 | 143582 | 265152.7 |
| 22 | 30.9801 | 82.2325 | Inner plateau | Arkok Tso | 58.428 | -0.087 | 0.283 | 214 | 30.980 | 82.232 | Arkok Tso | 0.0030 | 0.0030 | 5116 | 87351 | 12474.9 |
| 23 | 34.0106 | 82.3669 | Inner plateau | Arku Tso | 105.076 | 0.036 | 0.360 | 155 | 34.011 | 82.367 | Arku Tso | 0.1063 | 0.1063 | 4937 | 73756 | 2322.0 |
| 24 | 37.5462 | 89.3726 | Inner plateau | Ayakum Kul | 631.058 | 0.182 | 0.198 | 70 | 37.546 | 89.373 | Ayakum Kul | 0.0159 | 0.0160 | 3876 | 51255 | 24280.4 |
| 25 | 30.9367 | 89.6754 | Inner plateau | Bul Tso | 103.521 | 0.370 | 0.481 | | | | | | | 4656 | 88554 | 3406.7 |
| 26 | 31.8236 | 88.248 | Inner plateau | Chagut Tso | 87.861 | -0.040 | 0.388 | | | | | | | 4553 | 87008 | 15776.1 |
| 27 | 32.1953 | 87.7718 | Inner plateau | Chanjun Tso | 35.698 | 0.558 | 0.252 | | | | | | | 4647 | 86076 | 3476.5 |
| 28 | 34.0141 | 81.5995 | Inner plateau | Charol Tso | 346.353 | 0.312 | 0.212 | 153 | 34.014 | 81.599 | Charol Tso | 0.0226 | 0.0349 | 4812 | 76018 | 8454.2 |
| 29 | 31.3774 | 87.8936 | Inner plateau | Chikut Tso | 73.069 | -0.005 | 0.350 | 206 | 31.377 | 87.894 | Chikut Tso | 0.0006 | 0.0145 | 4648 | 87008 | 15776.1 |
| 30 | 31.9484 | 90.3365 | Inner plateau | Chodjari Tso | 29.200 | 0.293 | 0.312 | | | | | | | 4606 | 86244 | 1017.9 |
| 31 | 31.2766 | 83.4299 | Inner plateau | Chovo Tso | 181.928 | 0.114 | 0.207 | 210 | 31.277 | 83.430 | Chovo Tso | 0.0725 | 0.0725 | 4760 | 88211 | 2564.3 |
| 32 | 36.9781 | 95.2047 | Inner plateau | Dabsan Nor | 290.922 | 0.034 | 0.310 | 74 | 36.978 | 95.205 | Dabsan Nor | 0.0022 | 0.0028 | 2680 | 54119 | 109736.4 |
| 33 | 31.0601 | 86.601 | Inner plateau | Dangra Tso | 823.731 | 0.291 | 0.572 | 218 | 31.060 | 86.601 | Dangra Tso | 0.0167 | 0.0167 | 4535 | 88560 | 9018.0 |
| 34 | 36.1895 | 88.1413 | Inner plateau | Dekirpa Kul | 24.414 | 0.189 | 0.434 | | | | | | | 4877 | 57076 | 1090.8 |

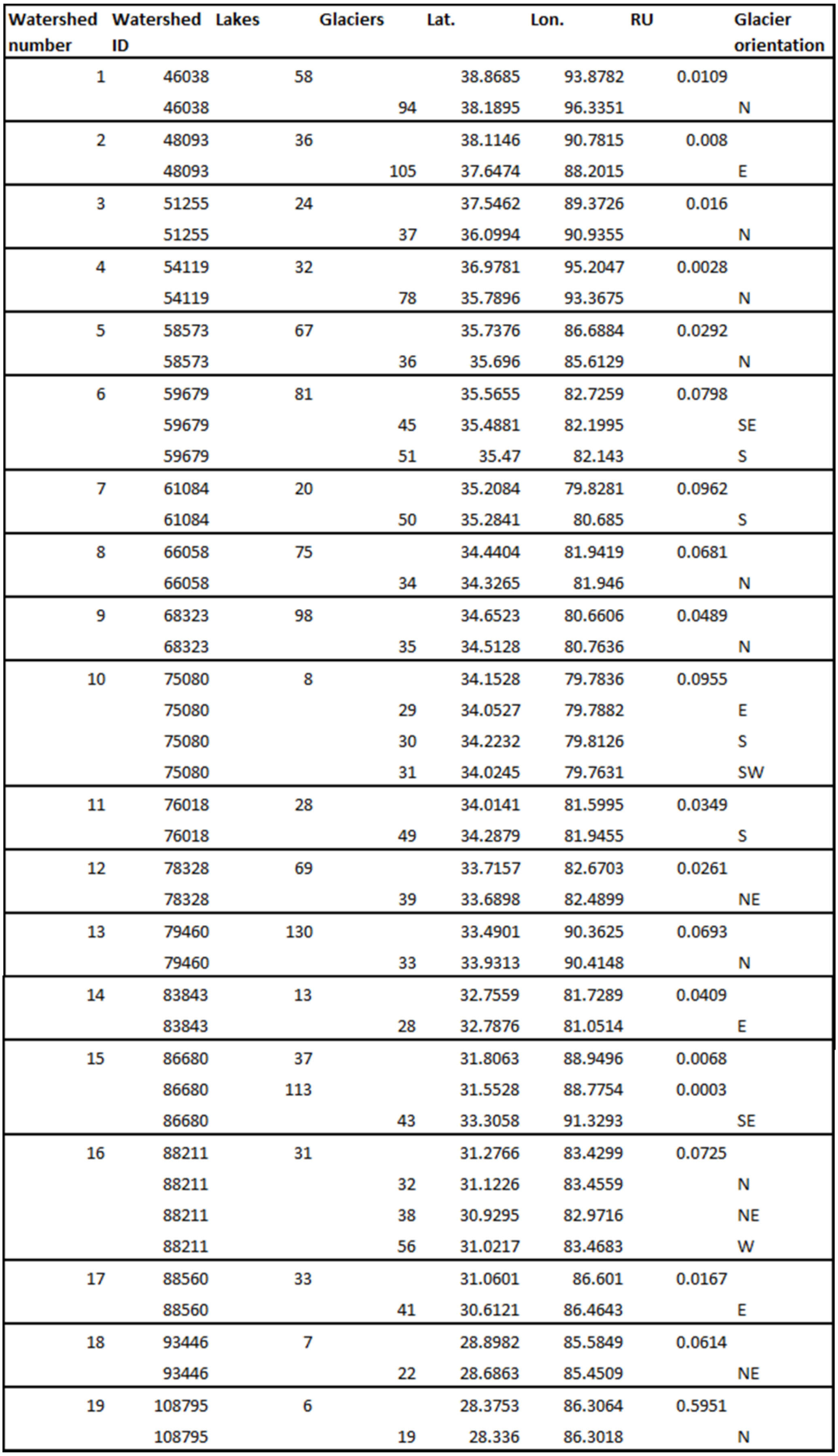
| ICESat lake data | | | | | Threshold = 15 cm | | | Geometric lake data | | | | | | Height SRTM | WaterSHEDS basin data | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Basin | Lake name | Area km^2 | Change m/yr | RMSE m | No. | Lat | Lon | Lake Name | RD | RU | Altitude m | BASIN_ID | AREA_KM^2 |
| 35 | 34.9514 | 81.5643 | Inner plateau | Echil Kul | 106.581 | 0.727 | 0.378 | 121 | 34.951 | 81.564 | Echil Kul | 0.0038 | 0.0367 | 4904 | 63178 | 3534.4 |
| 36 | 38.1146 | 90.7815 | Inner plateau | Gaekel Tso | 124.335 | 0.002 | 0.409 | 65 | 38.115 | 90.782 | Gaekel Tso | 0.0080 | 0.0080 | 2854 | 48093 | 24439.5 |
| 37 | 31.8063 | 88.9496 | Inner plateau | Garing Tso | 1821.133 | 0.680 | 0.338 | 197 | 31.806 | 88.950 | Garing Tso | 0.0068 | 0.0068 | 4539 | 86680 | 28955.9 |
| 38 | 34.4334 | 82.3369 | Inner plateau | Gore Tso | 23.049 | 0.387 | 0.386 | | | | | | | 5095 | 70933 | 639.0 |
| 39 | 31.7128 | 88.0035 | Inner plateau | Jagok Tso | 346.132 | -0.046 | 0.387 | 196 | 31.713 | 88.004 | Jagok Tso | 0.0002 | 0.0122 | 4554 | 87008 | 15776.1 |
| 40 | 35.581 | 91.1244 | Inner plateau | Kekexili Tso | 301.004 | 0.293 | 0.258 | 103 | 35.581 | 91.124 | Kekexili Tso | 0.0190 | 0.0349 | 4886 | 59346 | 2631.1 |
| 41 | 33.9487 | 80.902 | Inner plateau | Kenze Tso | 105.528 | 0.303 | 0.144 | 152 | 33.949 | 80.902 | Kenze Tso | 0.0634 | 0.0634 | 4525 | 76996 | 2491.3 |
| 42 | 38.3051 | 97.5962 | Inner plateau | Khara Nor | 586.663 | 0.158 | 0.163 | 63 | 38.305 | 97.596 | Khara Nor | 0.0195 | 0.0195 | 4076 | 47605 | 4745.9 |
| 43 | 31.1341 | 88.3068 | Inner plateau | Kyaring Tso | 476.197 | -0.012 | 0.655 | 215 | 31.134 | 88.307 | Kyaring Tso | 0.0058 | 0.0167 | 4649 | 87008 | 15776.1 |
| 44 | 32.0298 | 84.1162 | Inner plateau | Lakok Tso | 94.482 | 0.202 | 0.160 | 184 | 32.030 | 84.116 | Lakok Tso | 0.0095 | 0.0095 | 4467 | 85994 | 3671.6 |
| 45 | 35.7494 | 90.1903 | Inner plateau | Lexiewuda Tso | 224.935 | 0.394 | 0.169 | 96 | 35.749 | 90.190 | Lexiewuda Lake | 0.0311 | 0.0311 | 4870 | 58528 | 2028.5 |
| 46 | 30.9874 | 90.9674 | Inner plateau | Long Gyok Tso | 5.917 | 0.060 | 0.456 | | | | | | | 4737 | 88192 | 4804.1 |
| 47 | 35.6927 | 87.2537 | Inner plateau | Lotchuy Tso | 43.388 | 0.007 | 0.377 | | | | | | | 4848 | 58763 | 2456.7 |
| 48 | 34.1285 | 82.4155 | Inner plateau | Memar Tsaka | 17.622 | 0.430 | 0.394 | | | | | | | 4920 | 73756 | 2322.0 |
| 49 | 30.7176 | 90.6461 | Inner plateau | Nam Tso | 1963.637 | 0.230 | 0.388 | 223 | 30.718 | 90.646 | Nam Tso | 0.0311 | 0.0311 | 4724 | 88957 | 10711.8 |
| 50 | 31.8585 | 89.7844 | Inner plateau | Namka Tso | 21.230 | 0.360 | 0.689 | | | | | | | 4537 | 86462 | 1473.7 |
| 51 | 32.0817 | 90.8458 | Inner plateau | Namru Tso | 207.865 | 0.347 | 0.309 | | | | | | | 4568 | 85807 | 3500.3 |
| 52 | 36.7276 | 95.8222 | Inner plateau | huoluxun Tso | 4.108 | 0.003 | 0.468 | | | | | | | 2676 | 54119 | 109736.4 |
| 53 | 31.5404 | 83.1013 | Inner plateau | Nganglaring Tso | 498.912 | -0.002 | 0.369 | 201 | 31.540 | 83.101 | Nganglaring Tso | 0.0234 | 0.0238 | 4716 | 87351 | 12474.9 |
| 54 | 31.0223 | 87.1541 | Inner plateau | Ngangtse Tso | 390.244 | 0.398 | 0.285 | 216 | 31.022 | 87.154 | Ngangtse Tso | 0.0014 | 0.0014 | 4685 | 88509 | 7088.8 |
| 55 | 31.6226 | 82.3323 | Inner plateau | Ruldan Tso | 52.465 | 0.051 | 0.201 | 195 | 31.623 | 82.332 | Ruldan Tso | 0.0000 | 0.0025 | 4800 | 87150 | 1098.3 |
| 56 | 31.9977 | 88.2221 | Inner plateau | Sibung Tso | 60.121 | 0.353 | 0.120 | 186 | 31.998 | 88.222 | Sibung Tso | 0.0000 | 0.0028 | 4515 | 86076 | 3476.5 |
| 57 | 35.2208 | 90.3428 | Inner plateau | Sikin Ulan Nor | 210.571 | 0.391 | 0.336 | 114 | 35.221 | 90.343 | Sikin Ulan Nor | 0.0060 | 0.0121 | 4772 | 61105 | 6676.9 |
| 58 | 38.8685 | 93.8782 | Inner plateau | Sukai Nor | 102.235 | -0.022 | 0.461 | 62 | 38.869 | 93.878 | Sukai Nor | 0.0109 | 0.0109 | 2793 | 46038 | 20021.2 |
| 59 | 29.853 | 85.718 | Inner plateau | Tak Kyel Tso | 110.323 | 0.172 | 0.191 | 231 | 29.853 | 85.718 | Tak Kyel Tso | 0.0198 | 0.0198 | 5145 | 91502 | 767.0 |
| 60 | 31.1302 | 84.1304 | Inner plateau | Tarok Tso | 473.976 | 0.294 | 0.322 | 213 | 31.130 | 84.130 | Tarok Tso | 0.0250 | 0.0250 | 4567 | 87759 | 16773.4 |
| 61 | 30.9068 | 85.6178 | Inner plateau | Terinam Tso | 956.397 | 0.226 | 0.213 | 219 | 30.907 | 85.618 | Terinam Tso | 0.0065 | 0.0066 | 4612 | 88559 | 20011.8 |
| 62 | 34.8141 | 90.356 | Inner plateau | Ulan Ula Nor | 372.830 | 0.304 | 0.227 | 132 | 34.814 | 90.356 | Ulan Ula Nor | 0.0036 | 0.0057 | 4855 | 65622 | 6016.1 |
| 63 | 32.4582 | 89.9703 | Inner plateau | Yrna Tso | 149.804 | 0.475 | 0.352 | | | | | | | 4615 | 85015 | 2696.6 |
| 64 | 33.9478 | 82.9648 | Inner plateau | | 11.931 | 0.934 | 0.617 | 154 | 33.948 | 82.965 | | 0.0000 | 0.0004 | 4947 | 76903 | 3212.0 |
| 65 | 33.1693 | 89.0009 | Inner plateau | | 29.477 | 0.791 | 0.807 | 169 | 33.169 | 89.001 | | 0.0000 | 0.0074 | 4840 | 81411 | 3223.8 |
| 66 | 33.2255 | 88.4025 | Inner plateau | | 23.693 | 0.529 | 0.261 | | | | | | | 4756 | 81121 | 1106.3 |
| 67 | 35.7376 | 86.6884 | Inner plateau | | 50.534 | 0.495 | 0.387 | 98 | 35.738 | 86.688 | | 0.0292 | 0.0292 | 4882 | 58573 | 2305.4 |
| 68 | 36.0258 | 88.4931 | Inner plateau | | 17.412 | 0.470 | 0.467 | | | | | | | 4848 | 57704 | 682.2 |

| ICESat lake data | | | | | | Threshold = 15 cm | | Geometric lake data | | | | | | Height SRTM | WaterSHEDS basin data | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Basin | Lake name | Area km^2 | Change m/yr | RMSE m | No. | Lat | Lon | Lake Name | RD | RU | Altitude m | BASIN_ID | AREA_KM^2 |
| 69 | 33.7157 | 82.6703 | Inner plateau | | 19.809 | 0.420 | 0.454 | 159 | 33.716 | 82.670 | | 0.0261 | 0.0261 | 5061 | 78328 | 407.7 |
| 70 | 35.2087 | 90.1227 | Inner plateau | | 60.047 | 0.411 | 0.300 | | | | | | | 4772 | 61105 | 6676.9 |
| 71 | 31.5445 | 90.816 | Inner plateau | | 36.804 | 0.386 | 0.283 | | | | | | | 4598 | 87417 | 347.5 |
| 72 | 35.8049 | 89.4248 | Inner plateau | | 87.783 | 0.365 | 0.189 | 93 | 35.805 | 89.425 | | 0.0051 | 0.0051 | 4858 | 58367 | 1262.3 |
| 73 | 31.9382 | 87.0315 | Inner plateau | | 3.836 | 0.363 | 0.411 | | | | | | | 4470 | 86226 | 1428.5 |
| 74 | 33.8625 | 88.3007 | Inner plateau | | 44.946 | 0.363 | 0.167 | | | | | | | 4942 | 77625 | 1214.0 |
| 75 | 34.4404 | 81.9419 | Inner plateau | | 62.238 | 0.360 | 0.221 | 142 | 34.440 | 81.942 | | 0.0681 | 0.0681 | 5100 | 66058 | 2484.8 |
| 76 | 31.236 | 84.9686 | Inner plateau | | 105.690 | 0.352 | 0.398 | 212 | 31.236 | 84.969 | | 0.0157 | 0.0157 | 4623 | 88277 | 2433.3 |
| 77 | 31.5837 | 87.2801 | Inner plateau | | 55.658 | 0.345 | 0.087 | 198 | 31.584 | 87.280 | | 0.0020 | 0.0035 | 4605 | 86308 | 12834.6 |
| 78 | 35.563 | 90.1609 | Inner plateau | | 1.623 | 0.332 | 0.344 | | | | | | | 4908 | 60031 | 700.4 |
| 79 | 34.5734 | 87.3068 | Inner plateau | | 34.348 | 0.322 | 0.423 | 140 | 34.573 | 87.307 | | 0.0193 | 0.0193 | 4920 | 69053 | 3792.1 |
| 80 | 35.6087 | 90.3692 | Inner plateau | | 20.329 | 0.310 | 0.283 | | | | | | | 4908 | 60031 | 700.4 |
| 81 | 35.5655 | 82.7259 | Inner plateau | | 91.234 | 0.305 | 0.074 | 102 | 35.565 | 82.726 | | 0.0798 | 0.0798 | 5049 | 59679 | 1852.6 |
| 82 | 32.0245 | 83.9794 | Inner plateau | | 8.668 | 0.293 | 0.106 | | | | | | | 4472 | 85993 | 852.9 |
| 83 | 34.0518 | 85.6026 | Inner plateau | | 38.935 | 0.287 | 0.087 | | | | | | | 4880 | 76019 | 717.3 |
| 84 | 30.7517 | 85.9009 | Inner plateau | | 3.529 | 0.265 | 0.471 | | | | | | | 4688 | 88863 | 180.8 |
| 85 | 32.4737 | 83.2152 | Inner plateau | | 20.653 | 0.263 | 0.516 | | | | | | | 4433 | 84878 | 2890.6 |
| 86 | 35.5097 | 88.031 | Inner plateau | | 1.715 | 0.259 | 0.214 | | | | | | | 4883 | 60528 | 5076.9 |
| 87 | 32.1696 | 86.2048 | Inner plateau | | 9.042 | 0.256 | 0.524 | | | | | | | 4483 | 85656 | 2202.2 |
| 88 | 32.5081 | 83.2244 | Inner plateau | | 3.371 | 0.242 | 0.508 | | | | | | | 4430 | 84878 | 2890.6 |
| 89 | 35.5438 | 90.1652 | Inner plateau | | 1.692 | 0.236 | 0.146 | | | | | | | 4907 | 60031 | 700.4 |
| 90 | 34.6488 | 88.6904 | Inner plateau | | 67.276 | 0.227 | 0.324 | | | | | | | 4818 | 69359 | 7612.5 |
| 91 | 33.0117 | 89.7943 | Inner plateau | | 108.270 | 0.190 | 0.408 | | | | | | | 4872 | 82467 | 3727.4 |
| 92 | 33.3593 | 84.1909 | Inner plateau | | 35.954 | 0.184 | 0.295 | | | | | | | 4513 | 80328 | 3067.9 |
| 93 | 32.2507 | 83.2933 | Inner plateau | | 9.399 | 0.174 | 0.364 | | | | | | | 4676 | 84878 | 2890.6 |
| 94 | 34.8158 | 83.6308 | Inner plateau | | 1.313 | 0.169 | 0.417 | | | | | | | 4995 | 66213 | 2681.3 |
| 95 | 35.9872 | 90.1215 | Inner plateau | | 34.590 | 0.169 | 0.266 | | | | | | | 5002 | 51649 | 34097.5 |
| 96 | 35.7798 | 83.4635 | Inner plateau | | 11.159 | 0.160 | 0.347 | | | | | | | 4902 | 58432 | 1926.2 |
| 97 | 35.9931 | 88.1107 | Inner plateau | | 17.412 | 0.154 | 0.304 | | | | | | | 4841 | 57852 | 1784.5 |
| 98 | 34.6523 | 80.6606 | Inner plateau | | 2.720 | 0.148 | 0.166 | 128 | 34.652 | 80.661 | | 0.0489 | 0.0489 | 5140 | 68323 | 949.6 |
| 99 | 34.4326 | 83.5556 | Inner plateau | | 11.307 | 0.123 | 0.321 | | | | | | | 4918 | 75807 | 4951.2 |
| 100 | 31.4725 | 90.0344 | Inner plateau | | 1.369 | 0.123 | 0.427 | | | | | | | 4669 | 88192 | 4804.1 |
| 101 | 31.9315 | 82.7812 | Inner plateau | | 12.939 | 0.113 | 0.153 | | | | | | | 4964 | 86243 | 422.1 |
| 102 | 31.8613 | 83.1596 | Inner plateau | | 60.165 | 0.109 | 0.507 | 189 | 31.861 | 83.160 | | 0.0087 | 0.0143 | 4718 | 86495 | 2344.3 |

| ICESat lake data | | | | | | Threshold = 15 cm | | Geometric lake data | | | | | | Height SRTM | WaterSHEDS basin data | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Basin | Lake name | Area km^2 | Change m/yr | RMSE m | No. | Lat | Lon | Lake Name | RD | RU | Altitude m | BASIN_ID | AREA_KM^2 |
| 103 | 33.0216 | 83.9421 | Inner plateau | | 2.623 | 0.094 | 0.118 | | | | | | | 4554 | 82310 | 859.6 |
| 104 | 35.4136 | 90.9595 | Inner plateau | | 8.377 | 0.092 | 0.100 | | | | | | | 5014 | 61105 | 6676.9 |
| 105 | 33.5343 | 86.3397 | Inner plateau | | 2.636 | 0.066 | 0.570 | | | | | | | 4861 | 79073 | 480.3 |
| 106 | 35.2199 | 83.6794 | Inner plateau | | 6.839 | 0.060 | 0.568 | | | | | | | 4916 | 61085 | 787.8 |
| 107 | 35.1018 | 88.7404 | Inner plateau | | 1.982 | 0.036 | 0.179 | | | | | | | 5050 | 60756 | 6197.9 |
| 108 | 30.8356 | 88.0292 | Inner plateau | | 2.565 | 0.035 | 0.373 | | | | | | | 4873 | 87008 | 15776.1 |
| 109 | 34.0605 | 83.5017 | Inner plateau | | 1.268 | 0.032 | 0.029 | | | | | | | 4856 | 75886 | 280.9 |
| 110 | 34.204 | 87.795 | Inner plateau | | 14.310 | 0.022 | 0.374 | | | | | | | 4935 | 74754 | 1038.3 |
| 111 | 35.2911 | 87.2596 | Inner plateau | | 64.671 | 0.015 | 0.138 | | | | | | | 4744 | 60788 | 3329.2 |
| 112 | 36.9035 | 95.9502 | Inner plateau | | 92.946 | 0.012 | 0.136 | | | | | | | 2680 | 54119 | 109736.4 |
| 113 | 31.5528 | 88.7754 | Inner plateau | | 250.355 | 0.007 | 0.306 | 203 | 31.553 | 88.775 | | 0.0003 | 0.0003 | 4563 | 86680 | 28955.9 |
| 114 | 35.439 | 95.4182 | Inner plateau | | 7.991 | 0.005 | 0.510 | | | | | | | 4487 | 54119 | 109736.4 |
| 115 | 33.0185 | 82.5075 | Inner plateau | | 4.883 | -0.002 | 0.043 | | | | | | | 4468 | 82359 | 1518.8 |
| 116 | 33.9197 | 86.6872 | Inner plateau | | 23.478 | -0.003 | 0.473 | 156 | 33.920 | 86.687 | | 0.0085 | 0.0085 | 4822 | 77327 | 1067.9 |
| 117 | 37.0435 | 94.3903 | Inner plateau | | 13.550 | -0.008 | 0.059 | | | | | | | 2682 | 54119 | 109736.4 |
| 118 | 31.3837 | 88.7237 | Inner plateau | | 14.303 | -0.013 | 0.405 | | | | | | | 4566 | 86680 | 28955.9 |
| 119 | 30.9071 | 86.4082 | Inner plateau | | 3.231 | -0.014 | 0.444 | | | | | | | 4516 | 88560 | 9018.0 |
| 120 | 35.4827 | 83.7384 | Inner plateau | | 4.145 | -0.021 | 0.187 | | | | | | | 4797 | 60093 | 1716.0 |
| 121 | 36.9747 | 90.7316 | Inner plateau | | 18.195 | -0.047 | 0.358 | | | | | | | 4103 | 53872 | 864.9 |
| 122 | 35.035 | 84.4696 | Inner plateau | | 2.597 | -0.048 | 0.378 | | | | | | | 4934 | 60498 | 9497.4 |
| 123 | 30.6751 | 88.7936 | Inner plateau | | 1.385 | -0.074 | 0.124 | | | | | | | 4739 | 87008 | 15776.1 |
| 124 | 35.0689 | 90.273 | Inner plateau | | 13.545 | -0.090 | 0.362 | | | | | | | 4820 | 62135 | 1597.0 |
| 125 | 34.3417 | 91.5602 | Yangtze | Chamu Tso | 67.916 | 0.080 | 0.458 | | | | | | | 4675 | 86245 | 1910529.9 |
| 126 | 33.3782 | 89.8233 | Yangtze | Chibchang Tso | 378.746 | 0.573 | 0.338 | | | | | | | 4929 | 79790 | 3615.0 |
| 127 | 33.8862 | 91.1934 | Yangtze | Dzurhen Nor | 80.425 | 0.196 | 0.138 | | | | | | | 4922 | 77450 | 669.0 |
| 128 | 34.4211 | 91.0165 | Yangtze | Hulu Tso | 25.304 | 0.212 | 0.111 | | | | | | | 4788 | 86245 | 1910529.9 |
| 129 | 27.7052 | 100.777 | Yangtze | Lugu Tso | 52.533 | 0.010 | 0.245 | | | | | | | 2692 | 86245 | 1910529.9 |
| 130 | 33.4901 | 90.3625 | Yangtze | Mitijiangzhanmu Tso | 472.869 | 0.224 | 0.274 | 261 | 33.490 | 90.362 | Mitijiangzhanmu Tso | 0.0603 | 0.0693 | 4935 | 79460 | 9896.1 |
| 131 | 33.6337 | 89.7186 | Yangtze | | 62.978 | 0.402 | 0.365 | 251 | 33.634 | 89.719 | LuguTso | 0.0151 | 0.0151 | 4947 | 78639 | 1537.2 |
| 132 | 34.6517 | 94.0269 | Yangtze | | 2.406 | 0.335 | 0.203 | | | | MitijiangzhanmuTso | | | 4409 | 86245 | 1910529.9 |
| 133 | 33.7381 | 90.6389 | Yangtze | | 28.786 | 0.277 | 0.263 | | | | | | | 5000 | 79460 | 9896.1 |
| 134 | 35.2416 | 90.9234 | Yangtze | | 15.675 | 0.232 | 0.515 | | | | | | | 4844 | 86245 | 1910529.9 |
| 135 | 35.0347 | 91.5679 | Yangtze | | 6.496 | 0.199 | 0.440 | | | | | | | 4812 | 86245 | 1910529.9 |
| 136 | 32.957 | 93.5387 | Yangtze | | 8.478 | 0.171 | 0.548 | | | | | | | 4712 | 86245 | 1910529.9 |

| ICESat lake data | | | | | | Threshold = 15 cm | | Geometric lake data | | | | | | Height SRTM | WaterSHEDS basin data | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Lat. | Lon. | Basin | Lake name | Area km^2 | Change m/yr | RMSE m | No. | Lat | Lon | Lake Name | RD | RU | Altitude m | BASIN_ID | AREA_KM^2 |
| 137 | 34.1934 | 91.6963 | Yangtze | | 11.226 | 0.113 | 0.358 | | | | | | | 4649 | 86245 | 1910529.9 |
| 138 | 33.6687 | 90.88 | Yangtze | | 4.968 | 0.074 | 0.162 | | | | | | | 4979 | 86245 | 1910529.9 |
| 139 | 34.5987 | 92.4628 | Yangtze | | 18.128 | 0.046 | 0.498 | | | | | | | 4662 | 68454 | 630.9 |
| 140 | 32.8897 | 92.0667 | Yangtze | | 7.493 | 0.014 | 0.495 | 257 | 32.890 | 92.067 | | 0.0079 | 0.0079 | 5200 | 86245 | 1910529.9 |
| 141 | 34.3921 | 91.6983 | Yangtze | | 4.124 | -0.009 | 0.730 | | | | | | | 4709 | 86245 | 1910529.9 |
| 142 | 26.6221 | 100.667 | Yangtze | | 3.296 | -0.289 | 0.543 | | | | | | | 1500 | 98174 | 317.3 |
| 143 | 34.7813 | 98.2852 | Yellow River | Ayonggaima Tso | 21.931 | 0.191 | 0.424 | | | | | | | 4208 | 50123 | 761181.8 |
| 144 | 35.3069 | 99.1729 | Yellow River | Karar Nor | 47.884 | -0.078 | 0.065 | | | | | | | 4127 | 50123 | 761181.8 |
| 145 | 35.8123 | 103.196 | Yellow River | Luijiaxia Tso | 113.179 | 0.149 | 1.073 | 264 | 35.812 | 103.196 | LuijiaxiaLake | 0.0000 | 0.0009 | 1731 | 50123 | 761181.8 |
| 146 | 36.8896 | 100.182 | Yellow River | Qinghai | 4166.288 | 0.108 | 0.178 | 262 | 36.890 | 100.182 | Qinghai | 0.0011 | 0.0011 | 3194 | 54658 | 29568.6 |
| 147 | 34.914 | 97.2526 | Yellow River | Tsaring Tso | 525.092 | 0.177 | 0.291 | | | | LuijiaxiaTso | | | 4290 | 50123 | 761181.8 |
| 148 | 35.3018 | 97.0055 | Yellow River | | 5.385 | 0.456 | 0.423 | | | | Qinghai | | | 4535 | 50123 | 761181.8 |
| 149 | 34.9597 | 97.4744 | Yellow River | | 10.218 | 0.437 | 0.427 | | | | TsaringTso | | | 4290 | 50123 | 761181.8 |
| 150 | 36.8182 | 100.684 | Yellow River | | 98.050 | 0.189 | 0.295 | | | | | | | 3194 | 54658 | 29568.6 |
| 151 | 33.8554 | 102.142 | Yellow River | | 0.973 | 0.018 | 0.496 | | | | | | | 3430 | 50123 | 761181.8 |
| 152 | 34.8252 | 98.2572 | Yellow River | | 1.272 | -0.009 | 0.427 | | | | | | | 4208 | 50123 | 761181.8 |
| 153 | 36.1402 | 101.791 | Yellow River | | 24.252 | -0.012 | 0.848 | 263 | 36.140 | 101.791 | | 0.0000 | 0.0010 | 2163 | 50123 | 761181.8 |
| 154 | 36.1839 | 100.153 | Yellow River | | 3.809 | -0.248 | 0.364 | | | | | | | 2854 | 57077 | 1211.6 |

## Appendix B: Liked lakes and glaciers



| Watershed number | Watershed ID | Lakes | Glaciers | Lat. | Lon. | RU | Glacier orientation |
|---|---|---|---|---|---|---|---|
| 1 | 46038 | 58 |  | 38.8685 | 93.8782 | 0.0109 |  |
|  | 46038 |  | 94 | 38.1895 | 96.3351 |  | N |
| 2 | 48093 | 36 |  | 38.1146 | 90.7815 | 0.008 |  |
|  | 48093 |  | 105 | 37.6474 | 88.2015 |  | E |
| 3 | 51255 | 24 |  | 37.5462 | 89.3726 | 0.016 |  |
|  | 51255 |  | 37 | 36.0994 | 90.9355 |  | N |
| 4 | 54119 | 32 |  | 36.9781 | 95.2047 | 0.0028 |  |
|  | 54119 |  | 78 | 35.7896 | 93.3675 |  | N |
| 5 | 58573 | 67 |  | 35.7376 | 86.6884 | 0.0292 |  |
|  | 58573 |  | 36 | 35.696 | 85.6129 |  | N |
| 6 | 59679 | 81 |  | 35.5655 | 82.7259 | 0.0798 |  |
|  | 59679 |  | 45 | 35.4881 | 82.1995 |  | SE |
|  | 59679 |  | 51 | 35.47 | 82.143 |  | S |
| 7 | 61084 | 20 |  | 35.2084 | 79.8281 | 0.0962 |  |
|  | 61084 |  | 50 | 35.2841 | 80.685 |  | S |
| 8 | 66058 | 75 |  | 34.4404 | 81.9419 | 0.0681 |  |
|  | 66058 |  | 34 | 34.3265 | 81.946 |  | N |
| 9 | 68323 | 98 |  | 34.6523 | 80.6606 | 0.0489 |  |
|  | 68323 |  | 35 | 34.5128 | 80.7636 |  | N |
| 10 | 75080 | 8 |  | 34.1528 | 79.7836 | 0.0955 |  |
|  | 75080 |  | 29 | 34.0527 | 79.7882 |  | E |
|  | 75080 |  | 30 | 34.2232 | 79.8126 |  | S |
|  | 75080 |  | 31 | 34.0245 | 79.7631 |  | SW |
| 11 | 76018 | 28 |  | 34.0141 | 81.5995 | 0.0349 |  |
|  | 76018 |  | 49 | 34.2879 | 81.9455 |  | S |
| 12 | 78328 | 69 |  | 33.7157 | 82.6703 | 0.0261 |  |
|  | 78328 |  | 39 | 33.6898 | 82.4899 |  | NE |
| 13 | 79460 | 130 |  | 33.4901 | 90.3625 | 0.0693 |  |
|  | 79460 |  | 33 | 33.9313 | 90.4148 |  | N |
| 14 | 83843 | 13 |  | 32.7559 | 81.7289 | 0.0409 |  |
|  | 83843 |  | 28 | 32.7876 | 81.0514 |  | E |
| 15 | 86680 | 37 |  | 31.8063 | 88.9496 | 0.0068 |  |
|  | 86680 | 113 |  | 31.5528 | 88.7754 | 0.0003 |  |
|  | 86680 |  | 43 | 33.3058 | 91.3293 |  | SE |
| 16 | 88211 | 31 |  | 31.2766 | 83.4299 | 0.0725 |  |
|  | 88211 |  | 32 | 31.1226 | 83.4559 |  | N |
|  | 88211 |  | 38 | 30.9295 | 82.9716 |  | NE |
|  | 88211 |  | 56 | 31.0217 | 83.4683 |  | W |
| 17 | 88560 | 33 |  | 31.0601 | 86.601 | 0.0167 |  |
|  | 88560 |  | 41 | 30.6121 | 86.4643 |  | E |
| 18 | 93446 | 7 |  | 28.8982 | 85.5849 | 0.0614 |  |
|  | 93446 |  | 22 | 28.6863 | 85.4509 |  | NE |
| 19 | 108795 | 6 |  | 28.3753 | 86.3064 | 0.5951 |  |
|  | 108795 |  | 19 | 28.336 | 86.3018 |  | N |